U.S. Department of Commerce — National Bureau of Standards

RESEARCH PAPER RP725

Part of Journal of Research of the National Bureau of Standards, Volume 13, October 1934

INFLUENCE OF CHEMICALLY AND MECHANICALLY FORMED NOTCHES ON FATIGUE OF METALS

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ABSTRACT

An introductory section discusses the importance of stress concentration due to notches, as a cause of failures in service. Resistance of a notched specimen to fatigue and to impact may depend on entirely different properties. This paper considers the influence of notches on fatigue.

Section II considers the effect of chemically formed notches, attention being confined to the influence of pitting caused by stressless corrosion. Relationship between tensile strength and the percentage decrease in the fatigue limit for steels and aluminum alloys is illustrated by composite curves. Each of these curves is presumed to represent this relationship for a notch of fairly constant effective sharpness. The three-dimensional relationship between corrosion time, percentage damage, and tensile strength is illustrated and discussed.

The general object of section III is to determine whether composite curves of similar form may be obtained by a study of experimental data obtained by a number of investigators with mechanically formed notches. The fact that such graphs have been obtained, each representing the influence of one form of notch on one kind of metal, confirms the conclusion that a stressless corrosion graph of this type represents the influence of a notch of fairly constant effective sharpness. Reasons are discussed for the deviation of individual results from the ideal composite curve for a mechanically formed notch.

Section IV considers the relationship between notch sensitivity (as measured by percentage damage) and other properties of metals. The properties considered are: Hysteresis, ductility, and work-hardening capacity. Evidence is presented that scatter of individual results in a composite graph, of the type used, is due largely to differences in tensile work-hardening capacity. Evidence is also presented that notch sensitivity, while depending somewhat on elastic hysteresis, depends largely on work-hardening capacity.

Section V considers the influence of notches in diminishing the advantage of superior strength.

Section VI is a list of the selected references cited in the text.

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I. INTRODUCTION

The importance of stress concentration does not need emphasis to anyone who has examined a number of failed parts of structures and machines. In a collection of a number of failed shafts of naval vessels, for example, it was observed that the fracture invariably had started at a radial hole, such as an oil hole or screw hole. In any other collection of failed machinery parts, it would be found that fracture in each case had started in some region of stress concentration, such as a hole, thread, key way, notch, corroded surface, or some other region of abrupt change of section. This does not necessarily mean that such abrupt changes of section are in every case the chief cause of failure. It does mean, however, that these regions are sources of weakness, are at least contributory causes of failure, and in many instances the chief cause.

Designers, manufacturers, and users frequently do not realize the importance of such regions of stress concentration. If a hole, groove,

[2] Figures in parentheses here and throughout the text indicate references given in the list at the end of this paper.

keyway, or corrosion pit causes little reduction in cross section, the resultant loss of strength frequently is considered of little importance. This erroneous impression often is due to lack of knowledge of the entire subject of stress concentration. Even those who have some knowledge of theoretical stress concentration, however, often minimize its practical importance because of the fact that it is not usually important when the loading is static.

Under static loading, regions of high stress concentration are of only slight importance, unless the metal is brittle. Such regions usually are very small in comparison with the entire area of cross section. If, therefore, the metal is even moderately ductile, it merely yields slightly in regions of highest stress, with resultant partial relief of the stress concentration, and with practically no weakening of the entire structure or machinery part. The great majority of failures of machinery parts and some of the failures of structural parts, however, are due to many repetitions of a stress range. Under these conditions, the influence of holes, grooves, and other abrupt changes of section is of great importance. Such discontinuities lower the fatigue limit.

To save space, there is need for a single word as a general designation for all discontinuities, whether they be holes, notches, grooves or other depressions. For this purpose, the word "notch" will hereafter be used, a hole being considered as an internal notch.

Resistance of a notched specimen to fatigue and to impact may depend on entirely different physical properties. The properties of many machinery parts should be such as to give resistance to both fatigue and impact. In this paper, however, attention will be confined to the effect of notches on fatigue.

II. INFLUENCE OF CHEMICALLY FORMED NOTCHES ON FATIGUE OF METALS

1. INFLUENCE OF PRIOR STRESSLESS CORROSION ON THE STRESS-CYCLE GRAPH

In the course of an investigation of the combined influence of stress and corrosion, one of the authors has accumulated considerable data on the influence of prior stressless corrosion on fatigue. Recent correlation of the data has shown that the results are applicable to a study of the influence of notches on fatigue of metals. The use of chemically rather than mechanically formed notches in such a study, moreover, has some advantages, which will become apparent.

Investigation of the damaging effect of corrosion is essentially investigation of the effect of chemically formed notches. The effect of corrosion usually is due less to general loss of section than to stress concentration caused by corrosion pits. In considering the effect of corrosion pits, attention will here be confined to the influence of prior stressless corrosion. The influence of simultaneous stress and corrosion (stress corrosion or "corrosion fatigue") will not be considered.

Typical graphs [3] illustrating the influence of prior stressless corrosion on fatigue of carbon steels and ordinary alloy steels are shown in

[3] The word "graph" in this paper is used to denote all the graphical data relative to a single line or curve. The word includes in its meaning all the individual experimental points as well as the established line or curve. The word "diagram" is used to denote a series of graphs in the same figure.

figure 1. These are ordinary stress-cycle graphs redrawn on a more open scale from a figure in a previous paper by one of the authors (22). The 3 groups of graphs represent results obtained with a chrome-vanadium steel that had received 3 different heat treatments. The chemical composition of this steel (AZ) is given in table 1, details of heat treatment are given in table 2, and physical properties are given in table 3. The rotating-cantilever specimens used were of the tapered form described in previous papers by one of the authors (17, 18).

The uppermost curve in each group was obtained with uncorroded specimens. The other curves were obtained with specimens previously corroded in water for the times indicated at the right of the curves. The water used in these experiments was an ordinary well water, which was used extensively in previously described experiments by one of the authors (21, 22). As this water contained considerable calcium carbonate, it will hereafter be designated "carbonate water." After stressless corrosion for the indicated times in a stream of water, the specimens were dried, oiled, and subjected to fatigue tests, with the results illustrated in the figure.

The curves for previously corroded specimens, like the curves for uncorroded specimens, approach a horizontal asymptote. The lower part of each curve representing corroded specimens is approximately parallel to the curve representing uncorroded specimens. Because of this parallelism, only 1 or 2 specimens need be tested to establish the lower part of a curve, provided the specimens do not break at much less than a million cycles.

The greater the prior corrosion time, as illustrated in figure 1, the greater is the vertical distance between the curves representing corroded and uncorroded specimens. The lowering of the curve with increasing corrosion time is due to increasing stress concentration caused by increasing depth of corrosion pits.

The fatigue limit, which is the highest (nominal) cyclic stress that the specimen will endure without eventual failure, is represented by the ordinate of the horizontal asymptote of the stress-cycle curve. For steels, this limit is represented with sufficient accuracy by the ordinate of the curve at 10 million cycles. The lowering of the fatigue limit due to pitting may be used as a measure of the damage.

2. DECREASE IN THE FATIGUE LIMIT WITH CORROSION TIME

A useful type of graph may be obtained by plotting corrosion times against resultant fatigue limits. Examples of this type of graph, assembled from previous papers by one of the authors, are given in figure 2. Each curve in this figure represents the influence of time of prior stressless corrosion on the fatigue limit of a steel or other alloy. The ordinate of the origin of each curve represents the fatigue limit of the uncorroded alloy (endurance limit). The course of each curve represents the lowering of the fatigue limit with increasing corrosion time.

One of the curves represents stainless iron, 2 curves represent aluminum alloys, and the remainder represent carbon steels or ordinary alloy steels. Chemical compositions are given in table 1, details of heat treatment are given in table 2, and tensile properties are given in table 3. Unless otherwise stated, corrosion was in carbonate water at room temperature.

The curves for ordinary steels and for aluminum alloys are of the same general form. As illustrated by these curves, the rate of damage at first is rapid, but decreases with increasing corrosion time, and eventually becomes very slow. As illustrated by the group at the right of figure 2, the rates of damage in steam boiler water and in cool distilled water are less than in cool carbonate water. The relatively low rate of damage in boiler water (in spite of the high temperature) is due to low concentration of dissolved oxygen. The low rate in distilled water is due to low concentration of dissolved salts. Variables other than corrosion time evidently may influence greatly the rate of damage due to corrosion.

The behavior of alloys relatively resistant to corrosion is illustrated by the curve for stainless iron, JB–W–12. For a considerable time in contact with water the fatigue limit of this alloy is practically unaffected. Eventually, however, the fatigue limit begins to decrease, and falls at an increasing rate. Similar curves may be obtained with nickel, Monel metal, aluminum bronze, etc. A curve of this form has been called an "accelerated damage" curve. All the curves in figure 2 excepting the curve for stainless iron may be called "retarded damage" curves.

3. PERCENTAGE DAMAGE DUE TO CORROSION: RELATIONSHIP BETWEEN PERCENTAGE DAMAGE AND TENSILE STRENGTH

Because of the wide variation in physical properties of the metals, the stressless corrosion curves in figure 2 differ greatly in position and slope. For better comparison of the effects of corrosion on such widely differing metals, it is convenient to use another type of diagram, in which decreases in fatigue limit are expressed as percentages of the endurance limit. (By endurance limit is meant the fatigue limit obtained with smooth, uncorroded specimens.) By means of diagrams of this type, a study has recently been made of data obtained by stressless corrosion of a great variety of alloys in carbonate water. The experiments were made by one of the authors while at the U.S. Naval Engineering Experiment Station, Annapolis, Maryland. Results thus obtained have been published in various papers, but have not previously been studied with reference to percentage damage. Recent study of the data has shown that composite graphs may be constructed to represent relationship between percentage damage and tensile strength.

4. COMPOSITE GRAPHS FOR CARBON STEELS AND ORDINARY ALLOY STEELS

Composite graphs representing corrosion of carbon steels and ordinary alloy steels in carbonate water are shown in figures 3 and 4. Each symbol shown in the figures represents a result obtained with a steel of the indicated composition; each graph represents the damaging effect of corrosion for the indicated constant time. The curves have been drawn so as to give due weight to each experimental point. In view of the evident convergence of some of the curves toward the origin of coordinates, and for theoretical reasons, all the curves have been drawn so as to converge toward this same point. Such convergence being assumed, the approximate form and position of each curve are fairly well established. Moreover, the assembled curves, as shown in figure 4, form a consistent series.

The 10-day corrosion curve is best established. The scatter of experimental points for this graph varies with the strength of the steels. For the alloy steels with tensile strength greater than 120,000 lb, the scatter of experimental points is surprisingly small. For the steels with lower tensile strength, and especially for the carbon steels, the scatter is considerably greater. Wide scatter, however, is confined to only 5 of the 24 experimental points. Similar increase in scatter with decrease in tensile strength is found in the 25-day graph of figure 4 and the 50-day graph of figure 3. It is not surprising that scatter is greater for low-strength than for high-strength steels, because the experimental error in determination of the damage (difference between the fatigue limits of corroded and uncorroded specimens) increases with decrease in the tensile strength. For example, an error of only 1,000 lb/in.^{2} in determination of the fatigue limit of a soft steel might cause an error of more than one-fourth the estimated percentage damage. Although ordinary experimental errors may account for part of the scatter, however, a large part probably is due to another variable which will be discussed later.

These curves are believed to represent the average relationship between tensile strength and percentage decrease in the fatigue limit, due to constant corrosion intensity and constant time. The evidence seems to indicate that percentage damage depends largely on tensile strength. The rate of change of percentage damage with strength is large for low-strength steels, but decreases with increase in tensile strength. As Brinell hardness is approximately proportional to tensile strength, similar curves could be drawn to represent relationship between Brinell hardness and percentage damage.

The fact that pitting of carbon steels and ordinary alloy steels in water depends very little on composition or physical properties suggests the idea that each composite graph in figures 3 and 4 probably represents the influence of pits of nearly constant effective sharpness.[4] On this assumption, each curve would represent the increasing effect of a fairly constant notch with increase in tensile strength. (That this assumption is approximately correct is confirmed in section III by comparison of the curves representing stressless corrosion with curves representing mechanically formed notches.) Such curves, as they extend to the right, probably approach a horizontal asymptote, at an ordinate which may or may not correspond to the theoretical stress concentration factor.

5. THREE-DIMENSIONAL RELATIONSHIP BETWEEN CORROSION TIME, PERCENTAGE DECREASE IN FATIGUE LIMIT, AND TENSILE STRENGTH, FOR CARBON STEELS AND ORDINARY ALLOY STEELS

The assembled curves at the right of figure 4 illustrate, by their relative positions, the relatively great effect of the first few days' corrosion time and the gradually decreasing rate of damage with increase in corrosion time. Corrosion for 3 days evidently causes about half as much percentage damage as corrosion for 50 days, Corrosion for 10 days causes about five-sixths as much damage as corrosion for 50 days.

[4] The "effective sharpness" or "equivalent sharpness" of a notch depends not only on depth and radius of curvature, but also on relative and absolute size. The effect of a very small notch, for example, may be considerably less than that of a large notch with the same ratio of depth to radius of curvature. The effect of a corrosion pit, therefore, may depend more on the general shape than on the sharpness of minute salients.

The influence of corrosion time is better illustrated by the composite diagram in figure 5, which was developed from the diagram at the right of figure 4. Each curve in figure 5 represents the influence of corrosion time on percentage damage for steels having the indicated tensile strength. The form of each curve illustrates the initial rapid rate of damage and the gradual decrease in rate with time.

As the ordinate scales for the diagram in figure 5 and the diagram at the right of figure 4 are the same, these diagrams may be considered as two views of coordinate lines on a three-dimensional diagram. The top or plan view of this diagram is shown in figure 6. The curves in this figure may be considered as contour lines on a three-dimensional diagram. Each curve represents the relationship between tensile strength and corrosion time for the indicated constant percentage damage. For tensile strengths above about 180,000 lb the diagram is based on extrapolation of the diagrams in figures 4 and 5. The extrapolated portion of the diagram, however, is qualitatively, and probably not far from quantitatively, correct.

As illustrated by the course of the curves in figure 6, the corrosion time required to cause constant percentage damage decreases greatly with increase in tensile strength. The time required to cause 15-percent damage, for example, decreases from about 60 days to less than 1 day as the tensile strength is increased from 40,000 to 260,000 lb. The time required to cause 40-percent damage decreases from about 80 to 5 days as the tensile strength is increased from 120,000 to 260,000 lb. This diagram, therefore, illustrates the great importance of protecting steels of spring temper against the effect of even brief corrosion.

A contour line on the three-dimensional diagram does not represent constant effective sharpness of pitting. Constant effective sharpness of pitting is represented by a constant-time curve of the type shown in figures 3 and 4.

6. INFLUENCE OF PRIOR STRESSLESS CORROSION ON THE FATIGUE LIMIT OF ALUMINUM ALLOYS

Results of corrosion experiments with aluminum alloys are shown in figure 3 in comparison with results obtained with steels. The curves, drawn from the origin of coordinates so as to give due weight to each experimental point, are similar in form to the curves for steels. As shown by the relative positions of the curves, the percentage damage caused by 10 days' corrosion is more than half as great as the percentage damage caused by 50 or 100 days' corrosion. This time-damage relationship is in accordance with the form of the curve for aluminum alloys in figure 2. As there shown, the rate of damage is rapid at first, but gradually decreases, and after about 50 days is very slow.

The composite curves, drawn to represent the 10-, 50-, and 100-day results, apply properly only to the alloys that have not been cold-worked. As will be shown later, metals strengthened by cold working and metals strengthened by heat treatment, probably should not be represented by the same composite graph. The composite curves for aluminum alloys, like the composite curves for steels in figures 3 and 4, are intended to represent the effect of variation of tensile strength due to composition and heat treatment, not to cold working.

Most of the results for cold-worked aluminum and aluminum-manganese alloys, however, fall within the range of scatter of these graphs.

The 10-day curve for aluminum alloys, as illustrated in figures 3 and 4, is considerably above the 10-day curve for steels, and is even above the 200-day curve for steels. The 50-day curve for aluminum alloys is far above the 50-day curve for steels. Percentage damage due to corrosion, therefore, is considerably greater for aluminum alloys than for steels of the same tensile strength.

Each composite curve, for aluminum alloys as for steels, probably represents the influence of corrosion pits of practically constant effective sharpness. The slope of each curve, therefore, probably represents the increase in notch effect with tensile strength. (Notch effect for fatigue alone is under consideration.) The fact that the slopes of the curves are steeper for aluminum alloys than for steels could be due to either or both of two causes: (a) Greater effective sharpness of pitting in aluminum alloys than in steels; (b) greater notch sensitivity of aluminum alloys. Evidence presented in the following sections throws some light on the relative importance of these two factors.

III. INFLUENCE OF MECHANICALLY FORMED NOTCHES ON FATIGUE OF VARIOUS METALS AND ALLOYS

1. EFFECT OF A NOTCH ON THE FATIGUE LIMIT OF STEELS: DATA OF ONE OF THE AUTHORS

If each composite curve in figures 3 and 4 represents the influence of chemically formed notches of practically constant effective sharpness, curves of similar form should be obtainable by use of mechanically formed notches. Very little investigation of the effect of notches however, has been done in such a way as to supply the needed data. There have been some important investigations of the effect of notches of various sizes and shapes, with use of one or several alloys. But there has been very little investigation of the effect of notches of the same size and shape on metals having a wide range of composition and physical properties. The published results of investigation, moreover, are not easily evaluated, because the effect of a mechanically formed notch is influenced by several important variables. Perhaps the most important of these variables is the influence of the notch-forming process on the surrounding metal. A study of published data has been made however, on the basis of the relationship illustrated by the curves for chemically formed notches.

Results of previous experiments, made by one of the authors, have been found to throw some light on this subject. Most of these results have been presented in a previous paper (21) in the form of stress-cycle graphs. Percentage damage and its relation to physical properties, however, were not studied at that time. The experiments consisted in fatigue tests of notched and unnotched rotating-cantilever specimens. The notch was of the form and dimensions shown in figure 7. Special care was taken in the machining, and the radius of curvature at the bottom of the notch was checked microscopically.

Results obtained with carbon steels and ordinary alloy steels are represented in figure 7. The composition of each of the steels is given in table 1, details of heat treatment are given in table 2, and physical

properties are given in table 3. The numeral adjacent to each plotted symbol refers to the corresponding numeral in the first column of table 3.

A composite curve has been drawn so as to give due weight to each experimental point. Although these points are few and rather widely scattered, the evidence seems to indicate that the composite curve is similar in form to the curves obtained with chemically formed notches. The curve apparently points toward the origin of coordinates and, as it extends to the right, probably approaches a horizontal asymptote. The damaging effect of a mechanically formed notch evidently increases with the tensile strength, but at a gradually decreasing rate.

The horizontal asymptote may or may not represent, by its position, the theoretical percentage damage due to a notch of this form and relative size. As the notch used was rather large in relation to the diameter of the specimen, the theoretical percentage damage (based on the nominal stress in the minimum section) would be somewhat smaller than the theoretical percentage damage due to a relatively small notch. For a relatively small notch of this form, the theoretical stress concentration factor $\left(1+2\sqrt{\frac{d}{r}}\right)$ would be 11.6 and the theoretical percentage damage would be 91.4. The horizontal asymptote in figure 7, however, has been placed at a somewhat lower percentage, estimated from data on the effect of the same notch on copper.

2. EFFECT OF A NOTCH ON THE FATIGUE LIMIT OF COPPER: DATA OF ONE OF THE AUTHORS

The effect of a notch on the fatigue limit of copper is illustrated by the graph at the left of figure 7. This graph is based on results of experiments published in a previous paper by one of the authors (21). (In that paper, percentage damage and its relationship to physical properties were not considered.) The form and dimensions of the notch used are shown in the figure.

The lower of the two experimental points represents fully annealed material; the upper point represents cold-worked material. The relatively high positions of these two points seem to indicate that notch sensitivity of copper is high. Even for annealed copper, notch sensitivity evidently is equal to that of steels with tensile strength five times as great.

The curve has been drawn through the two experimental points and to the origin of abscissas. It has also been drawn so as to become practically horizontal at an abscissa corresponding to the "true-breaking stress", 76,000. (Reasons for so drawing the curve will be considered later.) The ordinate for this point may correspond to the theoretical percentage damage for a notch of this form and relative size, or to somewhat less than the theoretical percentage. The asymptote of the curve, however, evidently should be at a higher percentage than 76, the experimental value indicated in figure 7 for cold-worked copper. The asymptote should also be at a lower percentage than 91.4, the theoretical value for a relatively small notch. A percentage midway between these two values has been arbitrarily selected.

3. EFFECT OF A NOTCH ON THE FATIGUE LIMIT OF NICKEL-COPPER ALLOYS: DATA OF ONE OF THE AUTHORS (21)

The effect of a notch on the fatigue limit of nickel-copper alloys is illustrated by the graph at the right of figure 7. The notch used in investigation of nickel-copper alloys was the same in form and size as the notch used in investigation of steels and copper. The nickel-copper alloys represented in the figure range in composition from 21 percent nickel to commercially pure nickel. Some of the alloys were fully annealed; others were in work-hardened condition.

The same composite graph probably should not be used to represent both a range of properties due to variation in the degree of cold working and a range due to variation in composition and heat treatment. For this reason, no attempt has been made to draw a composite curve in figure 7 to represent the nickel-copper alloys. For comparison of positions, however, the composite curve for steels has been reproduced. By such comparison, in spite of the meagerness of the data and only approximate determination of some of the experimental points, it is possible to draw some conclusions about the notch sensitivity of these alloys.

For moderately work-hardened nickel and Monel metal, and for a slightly work-hardened alloy containing 40 percent nickel, notch-sensitivity evidently is about the same as for steels (not cold worked). For the alloys having 21 and 29 percent nickel, either annealed or moderately cold worked, notch sensitivity possibly is somewhat less than for steels.

4. EFFECT OF A NOTCH ON THE FATIGUE LIMIT OF STEELS: DATA OF HOUDREMONT AND MAILANDER

The effect of a small sharp notch on the fatigue limit of a number of steels with wide range of composition and physical properties has been investigated by Houdremont and Mailander (10). The notch used in their experiments was 0.1 mm deep and "as sharp as possible". No information, therefore, is available as to the ratio of depth of notch to radius of curvature. No clear information, moreover, is available in regard to the method of forming this notch.

Results of their experiments were represented in their paper by a diagram with coordinates similar to those in figures 3 and 7. The curves in their diagram, however, increase in slope with increase in tensile strength. Such curvature is not in accordance with theory, and is not an essential representation of their data. The results of their experiments, therefore, have been replotted and a composite curve has been drawn so as to approach the origin of coordinates and also to approach a horizontal asymptote. This graph is shown in figure 8, together with a miscellaneous collection of graphs representing results of experiments by a number of investigators, to determine the effect of notches, fillets, keyways, depressions, and surface roughness.

The curve representing results obtained by Houdremont and Mailander, drawn so as to give due weight to each experimental point, is almost identical with the 200-day corrosion curve, figures 3 and 4. Moreover, the scatter of experimental points in this graph, as in the graphs of figures 3 and 4, decreases with increase in tensile strength. In the group of points representing tensile strength be-

tween about 163,000 and 180,000 lb, which includes steels of various compositions and heat treatments, the scatter is surprisingly small. The scatter in such graphs, as previously stated, probably is due in part to the influence of another variable which will be discussed later.

Results obtained with austenitic steels, not shown in the figure, seem to indicate that mechanically formed notches cause much less percentage damage to austenitic steels than to carbon steels or ordinary alloy steels. A similar conclusion has been reached by Ludwik (14). Possible reasons for lower notch sensitivity of austenitic steels will be given later.

5. INFLUENCE OF A NOTCH ON THE FATIGUE LIMIT OF STEELS: DATA OF H. F. MOORE AND S. W. LYON

Results of experiments by H. F. Moore and S. W. Lyon (24) are shown in figure 9 (A). These authors used a rotating beam specimen with a groove of semicircular cross section. The steels used had a wide range of composition and physical properties. Because of the small number and wide scatter of experimental points, it is not possible to draw a composite curve on the basis of these points alone. For comparison, however, the 10-day corrosion curve in figure 3 has been reproduced in figure 9 (A). The position of the experimental points with reference to this curve is such as to indicate that an ideal curve based on a larger number of points probably would not differ greatly from the 10-day corrosion curve.

6. EFFECT OF A NOTCH ON THE FATIGUE LIMIT OF STEELS: DATA OF LUDWIK AND SCHEU

Results of experiments with a great variety of steels by P. Ludwik and R. Scheu (12,13,14) are represented in figure 9 (B). The diameter of the specimen was 9.5 mm; the notch was 0.2 mm deep, with root radius 0.05 mm.

The experimental points shown in the figure are widely scattered. The scatter decreases with increase in tensile strength, however, as in the graphs shown in figures 3, 4, 7, and 8. For comparison, the curves representing effects of 10, 25, 50, and 200 days' corrosion, established in figures 3 and 4, have been reproduced in figure 9 (B). Between the 10-day and 200-day curves are included 18 of the 25 experimental points; another point is only slightly below the 10-day curve. The remaining 6 points, which are considerably below the 10-day curve, are separated by a wide gap from the other 19. Results obtained by Ludwik and Scheu, therefore, are not in accord with results obtained by Houdremont and Mailander, as represented in figure 8, or with data in figures 3, 4, and 7. The data in figure 9 (B) apparently do not indicate a definite relationship between notch sensitivity and tensile strength.

It seems probable, however, that the positions of some, at least, of the experimental points in figure 9 (B) have been affected by one or more variables other than the physical properties of the alloy and the form and relative size of the notch. This conclusion is based on a study of the positions of the experimental points in comparison with the physical properties recorded by Ludwik (14). One example of such comparison may be cited. A low-carbon steel with tensile

strength about 42,000 lb is represented in the figure by an exceptionally low point, whereas 3 other low-carbon steels with tensile strength ranging from about 40,000 to 55,000 lb are represented by points much higher in the diagram. And yet the steel represented by the low point differs little in tensile properties from the other three steels. Similar comparison for the other exceptionally low points in the figure reveals no reason for the very low apparent notch sensitivity of these steels. The positions of some experimental points, therefore, probably have been influenced by one or more undesired variables.

Local work-hardening during the formation of the notch may account for these low points. Such strengthening of the metal around the notch, in the region of highest stress concentration, would raise the fatigue limit of the specimen and thus diminish the apparent damage. The fact that susceptibility to work-hardening during notch formation is greater for soft than for hard steels, may account for the exceptionally low notch sensitivity obtained by Ludwik and Scheu with some of their soft steels. No exceptionally low sensitivity was obtained with their hard steels.

The region of high stress concentration around a notch decreases in size with increase in sharpness and decrease in absolute size of the notch. The thin layer of metal work-hardened during notch formation, therefore, may include only a small part of the region of high stress concentration around a large notch, but may include all the region of high stress concentration around a small notch. Work-hardening during notch formation, consequently, may have little effect on the damage due to a large notch, but may greatly reduce the apparent damage due to a small notch. The small notch used by Ludwik and Scheu evidently would be especially susceptible to the effects of work-hardening during notch formation.

For the reasons mentioned, therefore, the exceptionally low points in figure 9 (B) probably should be given little weight in estimating the probable form and position of the composite curve. The upper boundary of the area covered by the experimental points probably represents (in qualitative curvature, though not in position) the ideal composite curve. This boundary is similar in form to the curves in figures 3, 4, and 7. A composite curve, giving full weight to all the experimental points in figure 9 (B), however, would correspond rather closely to the 25-day corrosion curve. If the exceptionally low points be disregarded, the composite curve would correspond approximately with the 50-day corrosion curve. If effects of local work-hardening during notch formation could be entirely prevented, the curve probably would be higher. For comparison with results obtained by other investigators, however, the composite curve has been given the form and position of the 50-day corrosion curve.

With austenitic steels (a valve steel and a stainless steel) not represented in figure 9, the percentages of damage obtained by Ludwik were 6 and 0, respectively. These low results are in general agreement with results obtained by Houdremont and Mailander. The evidence apparently indicates that notches are less damaging to austenitic steels than to other steels. The apparently low notch sensitivity of austenitic steels may be due, in part at least, to their high work-hardening rate or capacity. During notch formation, work hardening would be greater for austenitic steels than for other steels. Consideration will be given later to the possible influence of local hardening during a fatigue test.

7. MISCELLANEOUS DATA ILLUSTRATING THE INFLUENCE OF TENSILE STRENGTH ON NOTCH SENSITIVITY OF STEELS

Further evidence as to the forms of the ideal composite curves for steels is given in figure 8. Nine of the 13 miscellaneous curves in this figure, drawn so as to give due weight to each experimental point, are similar in form to the curves for corroded specimens in figures 3 and 4. They also form a consistent series. The other 4 curves in figure 8, each based on only 2 experimental points, are drawn so that all 13 curves form a consistent series, which (with practically no change) would fit into the series of stressless corrosion curves at the right of figure 4.

The evidence presented in figures 7, 8, and 9, therefore, confirms the assumption that each stressless corrosion curve in figures 3 and 4, represents the effect of a notch of practically constant effective sharpness. The curves in all these figures, consequently, illustrate average relationship between notch sensitivity and tensile strength of ordinary steels. The series of curves at the right of figure 4, moreover, illustrates the change in position and form of the curve, with change in effective sharpness of notch.

8. RELATIVE EFFECT OF NOTCHES ON TORSIONAL AND FLEXURAL FATIGUE. INFLUENCE OF FILLETS, KEYWAYS, AND SURFACE ROUGHNESS

Although the graphs in figure 8 were assembled primarily as confirmatory evidence for the forms of the ideal composite curves for steels, these graphs also illustrate other relationships of theoretical and practical importance. Although space is not available for adequate discussion, mention will be made of a few of these relationships.

The theoretical ratio between stress concentration factors due to torsion and tension (or bending) varies with the form of the notch. For a circumferential groove, the ratio is $\dfrac{1+\sqrt{\dfrac{d}{r}}}{1+2\sqrt{\dfrac{d}{r}}}$. For values of $\dfrac{d}{r}$ ranging from 1 to 9, this ratio ranges from $2/3$ to $4/7$. The corresponding ratio of percentage-decreases in the fatigue limit, however, ranges from 0.75 to about 0.84. Ratios of this order are obtained by comparison of corresponding ordinates for two pairs of curves (13, 14) in figure 8 (B). One of these pairs represents the influence of a sharp groove on torsional and flexural fatigue; the other pair represents the influence of a fillet. (Curve A has been reproduced from figure 9 (B).) The ordinate ratios for these 2 pairs are about 0.70 and 0.74, respectively. The evidence, therefore, confirms the theoretical conclusion that the effect of a circumferential groove or fillet is much less in torsional than in flexural fatigue.

For a transverse cylindrical hole in a cylindrical specimen, the theoretical ratio between torsional and flexural stress concentration factors is 4/3. Unlike a circumferential groove, therefore, such a hole should be slightly more damaging in torsional than in flexural fatigue. In agreement with theory, the torsional-fatigue curve 1 of figure 8 (A) is slightly higher in the diagram than the flexural-

fatigue curve in figure 9 (A) (which represents a $\frac{d}{r}$ ratio of 1.0), and is also slightly higher than the flexural fatigue curve of figure 8 (A), which represents the effect of a bored conical depression (1). The available evidence therefore, confirms the theoretical conclusion that a transverse cylindrical hole is slightly more damaging in torsional than in flexural fatigue.

A key way of the profile type, as illustrated in figure 8 (A) by 2 graphs representing results obtained by different investigators (5,29), apparently has much less effect in torsional than in flexural fatigue. In its relative effect on torsional and flexural fatigue, therefore, this longitudinal groove (in agreement with theory) evidently resembles more nearly a circumferential groove than a transverse cylindrical hole.

The influence of various methods of finishing the surface of a specimen is illustrated in figure 8 (A) by composite graphs (1, 23, 33). Space is not available for discussing this subject.

9. INFLUENCE OF A NOTCH ON THE FATIGUE LIMIT OF ALUMINUM ALLOYS; DATA OF LUDWIK AND SCHEU, AND OF R. R. MOORE

Ludwik and Scheu (12,13,14), using the same form of notch that they used for steels, investigated the effect of a notch on fatigue of aluminum alloys. R. R. Moore (26,27) also investigated the effect of a notch on aluminum alloys, using a groove 0.038 in. deep, with root raidus 0.01 in. The ratio $\frac{d}{r}$, therefore, was practically the same as for the notch used by Ludwik and Scheu. Results obtained in both investigations are included in figure 9 (C). For comparision, composite curves have been reproduced representing results obtained at Annapolis and results obtained by Ludwik and Scheu with steels.

Two experimental points in figure 9 (C) represent cold-worked alloys; the other experimental points represent alloys that were not in the cold-worked condition. As the influence of cold working and the influence of composition and heat-treatment on notch sensitivity probably should not be represented by the same composite curve, the 2 cold-worked alloys and the alloys that had not been cold-worked have been represented by 3 different curves, L, M, and N. Curve N representing severely cold-worked aluminum, is much steeper than curve L representing alloys not in the cold-worked condition. Curve M, representing an alloy that had been cold drawn after heat treatment, is only slightly steeper than curve L. These differences in slope between curves L, M, and N probably are due to differences in the degree of cold working received by the corresponding alloys. The evidence seems to indicate that increase in strength due to cold working causes greater increase in notch sensitivity than does the same increase in strength due to composition or heat treatment. Additional evidence on this subject will be presented later.

The scatter of results obtained by Ludwik and Scheu with aluminum alloys, as represented by graph L, is as great as the scatter obtained by the same investigators with steels. For reasons previously discussed, however, some of the experimental points probably are too low. With annealed duralumin, for example, percentage damage

obtained was 33.3. With duralumin hardened by heat treatment, however, percentage damage was only 3.5. With another hardened alloy differing little in composition from duralumin, percentage damage was 40.0. The percentage damage obtained with hardened duralumin, therefore, probably is much too small. For these reasons, the composite curve representing alloys that were not in the cold-worked condition has been drawn with little regard for the three exceptionally low experimental points.

This curve is far above the curve for steel specimens with the same notch ratio, and is even slightly above the curve for steel specimens with much sharper notch. Notch sensitivity of aluminum alloys, therefore, seems to be as great as the sensitivity of much stronger steels. The relative steepness of slope of the stressless-corrosion curves for aluminum alloys in figures 3 and 4, consequently, appears to be due chiefly to relatively great notch sensitivity rather than to sharper corrosion pitting.

10. INFLUENCE OF A NOTCH ON THE FATIGUE LIMIT OF MAGNESIUM ALLOYS: DATA OF R. R. MOORE

Results obtained by R. R. Moore (25,26) with magnesium alloys, using the same form of notch that he used with aluminum alloys, are shown in figure 9 (D). In the same figure are reproduced composite curves representing results obtained by other investigators with steels.

A composite curve to represent the results obtained with magnesium alloys has been drawn from the origin of coordinates through the mean position of the experimental points: The curvature has been made to correspond with that of the curves for steels. The curve for magnesium alloys is far above the curve representing the effect of a notch of about the same shape on steels, and is even above the curve for steel specimens with a much sharper notch.

Notch sensitivity for magnesium alloys, therefore, probably is at least as great as for aluminum alloys, and is as great as the sensitivity of much stronger steels.

IV. NOTCH SENSITIVITY AND ITS RELATIONSHIP TO OTHER PROPERTIES OF METALS

1. NOTCH SENSITIVITY

Various quantitative indices of notch sensitivity have been proposed. Some of these are based on relationship between actual and theoretical damage. The theoretical stress concentration factor, however, is not readily estimated, because of the influence of relative and absolute size of notch. The percentage decrease in the fatigue limit, due to a notch, is used in this paper as an index of notch sensitivity. Relative notch sensitivities are indicated by the relative magnitudes of the ordinates in diagrams of the type shown in figures 3, 4, 7, 8, and 9. In any such comparison, however, consideration must be given to differences in sharpness of notch and kind of stress.

2. NOTCH TOUGHNESS

Notch toughness probably should not be considered as the opposite of notch sensitivity, but as a combination of 2 variables, notch sensitivity and strength. Of two metals with equal notch sensitivity, the

stronger metal should be considered the tougher. To decide whether a weak metal with low notch sensitivity is tougher or less tough than a strong metal with high notch sensitivity, however, may be difficult. Nevertheless, a generally useful index of notch toughness of a metal (as illustrated by a diagram of the type shown in fig. 9) is the angle between the vertical and a line drawn from the origin of coordinates to the corresponding experimental point. Notch toughness increases with this angle. In any such comparison of metals, however, consideration must be given to differences in sharpness of notch and kind of stress.

Comparison of all the metals represented in figures 7 and 9 indicates that notch toughness is considerably less for copper, aluminum alloys, and magnesium alloys than for ordinary steels. For ordinary nickel-copper alloys with nickel content ranging from that of commercial nickel down to 20 percent or possibly less, as shown in figure 7, notch toughness probably is no less than for ordinary steels. For corrosion-resistant steels, as indicated by the data of Houdremont and Mailander (10) and also by data obtained by Ludwick (14), notch toughness evidently is greater than for carbon steels and ordinary alloy steels.

3. RELATIONSHIP OF NOTCH SENSITIVITY TO DUCTILITY

Notch sensitivity tends to decrease with increase in ductility. This general relationship between notch sensitivity and ductility is sometimes attributed to a surmised influence of ductility in favoring local yielding and consequent relief of stress concentration. It does not seem probable, however, that the degree of relief of stress concentration would depend on the ductility as measured by total deformation at fracture. There are reasons for doubting, moreover, that notch sensitivity depends largely on ductility as such, though it may depend on another property that is roughly proportional to total tensile elongation.

4. RELATIONSHIP OF NOTCH SENSITIVITY TO MECHANICAL HYSTERESIS

Attempts have been made recently to correlate notch sensitivity with mechanical hysteresis. Extensive investigation of this subject has been made by O. Foppl and his coworkers at the Wohler Institute. (The terms "damping capacity", and "dynamic ductility", used by these investigators, have no apparent advantage over the older name, mechanical hysteresis.)

According to the views of Foppl and his associates (11), high hysteresis value is accompanied by low notch sensitivity and vice versa. Data presented in support of this idea, however, are not conclusive. Although examples that apparently support the idea have been pointed out, there are also many discrepancies. For one such example, mention may be made of annealed copper. Although notch sensitivity of this metal is high, hysteresis also is high.

Hysteresis depends not only on the composition of the metal, on the mechanical and thermal treatment, and on the applied stress range, but also on the previously applied cycles of stress. The variation of hysteresis with stress range and with repetition of stress, has been studied by a number of investigators (2,4,6,8,11,15,16).

With repetition of cycles at constant stress range, hysteresis may increase at a decreasing rate, so as to approach a maximum; or it may decrease at a decreasing rate from the initial value (which may be large) to a minimum. For some metals, this minimum may possibly be an equilibrium value, which will prevail for an indefinitely large number of cycles. According to published results of experiments continued for many cycles, however, hysteresis sometimes may increase again at a decreasing rate. Both the decrease in hysteresis and the decrease in the rate of increase, are due to hardening of the metal under cyclic deformation. Moreover, the rate of hardening caused by cyclic deformation, like the rate of hardening caused by continuous deformation in one direction, continually decreases.

Increase of hysteresis at a decreasing rate, may occur whether or not the stress is above the fatigue limit. If the stress is above the fatigue limit, hysteresis eventually begins to increase at an increasing rate, and thus continues until the specimen fails. If the stress is below the fatigue limit, however, hysteresis eventually reaches a maximum and thereafter may slowly decrease. Such final decrease from a maximum probably is not uncommon. Haigh (8) has observed instances of increase during several million cycles, followed by slow decrease during about 30,000,000 cycles. Ludwik (14) has published curves illustrating the changes in hysteresis with cyclic stress at the fatigue limit. As indicated by a series of curves representing a great variety of annealed carbon steels, hysteresis first increased to a maximum and then gradually decreased. The number of cycles required to reach the maximum varied more than a hundredfold, with the carbon content of the steel. The gradual decrease from the maximum continued far beyond 10,000,000 cycles, and in some instances an equilibrium value had not been reached after a hundred million cycles.

Eventually, under cyclic stress at or below the fatigue limit, hysteresis reaches a value that thereafter remains constant. This condition is known as "elastic hysteresis." As shown by several investigators (9, 32), elastic hysteresis is appreciable even under very minute stress. As the relationship between initial hysteresis and elastic hysteresis (at the fatigue limit) differs greatly for different metals, comparison of initial hysteresis values for various metals, gives no means of comparison of elastic hysteresis values.

In a notched specimen, hysteresis causes the stress concentration to be less than the theoretical value. This effect of hysteresis, therefore, causes the fatigue limit of a notched specimen to be relatively high, and thus decreases the notch sensitivity. Elevation of the fatigue limit due to the stress-lowering effect of hysteresis, however, probably depends less on the initial hysteresis than on the elastic hysteresis at the fatigue limit. Initial hysteresis, as it gives no information about elastic hysteresis, cannot be used as a measure of notch sensitivity.

5. RELATIONSHIP OF NOTCH SENSITIVITY TO WORK-HARDENING DUE TO CYCLIC STRESS

Although stress lowering due to elastic hysteresis doubtless has some effect on notch sensitivity, another influence of cyclic stress may have greater effect. The effect of a notch on the fatigue limit may depend not only on the stress concentration, but also on the amount

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of local work-hardening accompanying the progress from initial to elastic hysteresis.

Although all metals are more or less work-hardened by cyclic stress at the fatigue limit, the strengthening influence is most conspicuous for fully annealed metals and single-phase alloys. For such materials, the fatigue limit is far above the initial elastic limit, and is even above the initial tensile proof stress. (By "proof stress" is meant the stress that, after release of load, will result in permanent elongation of 0.0001 in. per inch length). During the progress from initially large hysteresis to elastic hysteresis, the metal in the most highly stressed parts of the specimen is work-hardened, and the elastic range is increased until it practically coincides with the fatigue range (within the limitations of elastic hysteresis).

The amount and distribution of the work-hardening during the progress from initial to elastic hysteresis, however, depend not only on the fundamental properties of the metal and on the nominal cyclic stress, but also on the specific conditions that determine the constancy or variation of the actual stress and strain throughout the test. For this reason, the fatigue limit is not a fundamental property of the metal, but depends somewhat on the impressed conditions of the test. By gradual increase of stress from below the ordinary fatigue limit, the limit may be raised. Even by cyclic stress above the fatigue limit (as indicated by unpublished results of experiments by one of the authors), it appears possible that the fatigue limit may be raised, provided the number of cycles of overstress is less than a critical value, which depends on the metal and on the overstress. The specific conditions in a fatigue test often are such that the actual stress increases while the nominal stress remains constant. In a rotating-beam specimen, for example, the progress from initial to elastic hysteresis is accompanied by a change in stress distribution. As the final change in hysteresis (when the nominal stress is just below the fatigue limit) probably always is a decrease, the stress distribution from axis to circumference becomes more nearly linear, and the stress at the circumference thus approaches the fatigue limit from below. For this reason, the fatigue limit obtained by rotating-beam test theoretically would be higher than that obtained by direct tension-compression test. The idea that the fatigue limit is appreciably influenced by the specific conditions of the test, moreover, is supported by evidence based on experiments of a number of investigators.

The stress gradient in a rotating-beam specimen makes possible a gradual rise of actual stress to the fatigue limit. A more pronounced rise to the fatigue limit probably results from the steeper stress gradient around a notch. Local elevation of the fatigue limit due to rising cyclic stress, therefore, tends to be greater in a notched than in an unnotched specimen. The greater this local elevation of the fatigue limit, the steeper is the hardness gradient opposing the influence of the stress gradient and thus decreasing the apparent notch sensitivity.

6. TENSILE WORK-HARDENING CAPACITY

The steepness of the hardness gradient around a notch possibly depends on the work-hardening capacity of the metal. According to this view, therefore, notch sensitivity depends considerably on

work-hardening capacity. The rate of increase of hardness with cold work would influence the amount of work-hardening per cycle, and thus would determine the number of cycles necessary for hardness to reach its maximum. Though maximum hardness may depend somewhat on the amount of work-hardening per cycle, however, it probably depends much more on work-hardening capacity. Notch sensitivity, therefore, probably depends less on rate of work-hardening than on work-hardening capacity.

To determine whether there is experimental evidence of significant relationship between work-hardening capacity and notch sensitivity, it is necessary to compare corresponding values of these two properties for a great variety of metals and alloys. Some evidence on this subject is available, based on notch effects of stressless corrosion and on the corresponding "tensile work-hardening capacities." These data, obtained by one of the authors while employed at the U.S. Naval Engineering Experiment Station, have recently been compared and correlated. The results of the correlation are presented in table 3 and in figures 10 and 11.

Tensile work-hardening capacity may be estimated by comparing some other tensile property with the maximum stress obtainable in tension, the true breaking stress (actual breaking load divided by the sectional area at fracture). For comparison with the true breaking stress, the proof stress was tried, but the relationship proved too erratic. Tensile strength finally was chosen for this purpose. After trial of various indices based on the relationships between the two properties, the index finally chosen was the percentage ratio of tensile strength to true breaking stress; this ratio will be called the "percentage strength." Maximum hardness obtainable by pure tensile stress (hardness independent of cold working previous to the tension test) is thus considered as 100 percent. Percentage strength subtracted from 100 evidently may be used as a direct index of work-hardening capacity.

7. RELATIONSHIP BETWEEN PERCENTAGE STRENGTH, WORK-HARDENING CAPACITY, AND TENSILE STRENGTH

Relationship between percentage strength and tensile strength, for a great variety of metals and alloys, is illustrated in figures 10 and 11. Ordinates measured from the bottom of the figure represent percentage strength; ordinates measured from the top represent work-hardening capacity.

The straight broken lines in figures 10 and 11 represent the influence of cold work on the relationship between tensile strength and work-hardening capacity. The intersection of each of these lines with the line representing zero work-hardening capacity is at an abscissa representing the true breaking stress; each of these intersections represents a metal or alloy that has been cold-worked (by tension) until the tensile strength equals the true breaking stress. Because of the relationship between ordinate and abscissa in a diagram of this type, the lines point toward the origin of coordinates. In figure 10, the graphs represent results of tension tests on metals that (at the beginning of the test) were not work-hardened. In figure 11, the graphs represent results of tests of both annealed and cold-worked metals.

The broken lines in figure 11, with two exceptions, represent nonferrous metals. The two exceptions are lines representing results obtained by O'Neill (28) with two samples of steel wire. These wires were cold-drawn to various degrees of hardness and an ordinary tension test was made at each stage. The true breaking stress, as O'Neill expected, was practically independent of the amount of previous cold drawing. The straight lines in figure 11 are drawn to the average values of the true breaking stress.

The lowest plotted symbol, for each of the metals represented in figure 11, is based on the result of a tension test of fully annealed metal; each higher plotted symbol represents the result of a tension test of metal that had been previously cold-worked.

The true breaking stress obtained with cold-worked metal, as shown in table 3, is sometimes higher and sometimes lower than that obtained with fully annealed metal. The differences, though sometimes rather large, are no greater than would be expected in view of the difficulty of obtaining an accurate value for this property.

As the metals represented in figure 10 had not been work-hardened, differences in physical properties depend on differences in composition and heat treatment. The steels represented in this figure include those represented in figure 3, in the graph showing the effect of 10 days' stressless corrosion. They also include additional steels, most of which were tested at the U.S. Naval Experiment Station; properties of a few of the steels of highest strength were obtained from data published by Gillett and Mack (3). The composite curve drawn to represent the relation between percentage strength and tensile strength for carbon steels and ordinary alloy steels, is similar in form to curves representing the relation between tensile strength and notch sensitivity. Best comparison can be made with the curve in figure 3 representing the notch effect of 10 days' stressless corrosion. To facilitate comparison of corresponding experimental points in the 2 figures, each steel represented in figure 3 has been given an identification number, and the same numbers have been placed beside corresponding symbols in figure 10. These numbers are also listed in the first column of tables 2 and 3.

Prior to comparison of these 2 graphs, it had been assumed that the scatter of individual points in figure 3 is due chiefly to the unavoidable variations in intensity of corrosive attack, and to the natural scatter of points representing differences between the fatigue limits of corroded and uncorroded specimens. Comparison of the relative positions of the corresponding experimental points in the 2 graphs, however, apparently reveals some relationship between variations in notch sensitivity and variations in work-hardening capacity. The most striking relationship is between points 2, 3, 7, and 8 of the 2 figures. Each pair connected by a broken line represents the same sample of steel after 2 different heat treatments. Points 2 and 7 represent fully annealed steels; points 3 and 8 represent the same steels quenched and tempered. The position of these 2 pairs of points with reference to the composite curve in each figure is about the same. That this relationship is not due to chance appears probable, moreover, when comparison is made between the other corresponding points in the 2 figures. The distribution of 16 of the 24 points, above and below the composite curve in each figure, is qualitatively the same. Of the remaining 8 points, 2 are practically on the composite curve

in one of the figures. The fact that at least two-thirds of the points are similarly distributed with reference to the composite curve seems to indicate that the form of the composite curve and the variations in position of the experimental points depend somewhat on work-hardening capacity.

As indicated by the position of the 2 symbols representing corrosion-resistant steels, the percentage strength of these austenitic steels is considerably less than that of ordinary steels. The relatively low percentage strength (high work-hardening capacity) of these steels evidently corresponds qualitatively to their lower notch sensitivity.

Although the symbols representing aluminum alloys are widely scattered, a composite curve has been drawn to represent the average relationship between percentage strength and tensile strength. This curve is considerably above the curve representing steels. The relative positions of these 2 curves evidently are in accordance with the lower notch-toughness of aluminum alloys, illustrated in figure 9.

Figure 12 illustrates the relationship between tensile strength and the percentage elongation at fracture (in 2-inch gage length). The metals represented here are the same that are represented in figure 10. To facilitate comparison between figures 3, 10, and 12, identification numbers have been given to corresponding symbols. The curves in figure 12, if inverted, evidently would be similar to the corresponding curves in figure 10. This similarity, however, merely illustrates the fact that tensile elongation is a rough index of work-hardening capacity. It does not decide the question whether notch sensitivity is dependent chiefly on ductility as such, or on work-hardening capacity. Some evidence relative to this question, however, is obtained by comparing the distribution of individual results in figures 3, 10, and 12. The relative positions of symbols 2, 3, 7, and 8, which have been shown to be in good agreement in figures 3 and 10, are in poor agreement in figures 12 and 3. Less than half the numbered symbols in figure 12, moreover, are distributed conformably to those in figure 3, with reference to the composite curve. Comparison of figure 12 with figures 3 and 10, therefore, leads to the conclusion that notch sensitivity probably is more nearly related to percentage strength than to total elongation.

Relationship between elongation at maximum load (point of necking) and tensile strength, for the same metals and alloys, has been studied by means of a diagram not here shown. The curves in this diagram are similar in form to the curves in figure 12. The distribution of individual results, however, is little better than the distribution in figure 12. Notch sensitivity, therefore, appears to be more nearly related to percentage strength than to elongation at maximum load.

Because the straight broken lines in figure 11 converge toward the origin of coordinates, their slopes must decrease with increase in the true breaking stress. With the slopes of these straight lines may be compared the varying slope of the composite curve for steels, which has been reproduced in figure 11 as curve A. This curve, representing the influence of composition and heat treatment, differs greatly in slope and form from the lines representing the influence of cold working. The straight lines, at their intersections with curve A, are much steeper than this curve. The rate of decrease in work-hardening capacity with increase in strength, therefore (as might be

expected), is much greater when due to cold working than when due to composition or heat treatment.

If notch sensitivity depends largely on work-hardening capacity, increase in strength due to cold working evidently would cause greater increase in notch sensitivity than would the same increase in strength due to composition or heat treatment. This means that curves of the type shown in figures 3, 4, 7, and 9 would be steeper when they represent the influence of cold working than when they represent the influence of composition or heat treatment. Experimental evidence on this subject, though meager, seems to support the hypothesis. The curve for cold-worked aluminum in figure 9 (C), for example, is much steeper than the curve for aluminum alloys not cold worked. The curve for an aluminum alloy that had been cold drawn after heat treatment, moreover, is above the curve representing alloys that had not been cold worked. Although a separate curve for extruded magnesium has not been drawn in figure 9 (D), it is possible that this metal had received more cold work than the extruded or forged magnesium alloys. If this surmise is correct, the relatively high position of the point representing extruded magnesium is due to decreased work-hardening capacity caused by cold working. A few results obtained by Haigh and Beale (7) with cold-rolled strip steel, when compared with the curve in figure 7 representing steels that had not been cold worked, constitute additional evidence pointing in the same direction.

The relative positions of the composite curve for steels, the lines for aluminum alloys, and the point representing magnesium alloys are about the same in figures 10 and 11 as in figures 4 and 9. The relative position of the line for copper, moreover, is about the same in figure 11 as in figure 7. The available evidence seems to indicate that the general distribution of experimental points and lines for various metals and alloys in a percentage-strength diagram is qualitatively similar to the distribution of corresponding points and lines in a notch-sensitivity diagram. The only apparent discrepancies are in the positions of individual points representing fully annealed metals.

The high notch sensitivity of cold-worked copper is in accordance with the high percentage strength, as illustrated in figures 7 and 11, respectively. For fully annealed copper, however, notch sensitivity is too high to be in accordance with the percentage strength. For the other fully annealed metals and single-phase alloys represented in figure 11, moreover, percentage strength is not high; for some of these, in spite of their relatively high tensile strength, percentage strength is lower than for copper. And yet notch sensitivity of these metals, according to the meager evidence available, is not low. As shown in figure 7, for example, notch sensitivity is not much less for annealed nickel-copper alloys than for steels of the same strength. All these apparent exceptions to the general rule that notch sensitivity is closely related to percentage strength are metals whose fatigue limits are above (sometimes far above) their elastic limits. For annealed copper the fatigue limit is more than twice the tensile proof stress. Even for copper specimens with a sharp notch, as shown in a paper by one of the authors (21), the fatigue limit is higher than anything that could be called an elastic limit.

The fatigue limit of a fully annealed single-phase metal is essentially the fatigue limit of metal that has been considerably work-hardened.

In the most highly stressed part of a notched or unnotched specimen of such metal, after repeated stress at the fatigue limit, there is a layer of work-hardened metal. The hardened layer around a notch probably is much thicker in an annealed single-phase metal than in a metal whose fatigue limit does not greatly exceed the elastic limit. The work-hardening capacity of the metal in this layer is not the work-hardening capacity of fully annealed metal but has been considerably reduced by the cyclic deformation. (The rapidity of loss of work-hardening capacity with plastic deformation is illustrated by the fact that copper loses the greater part of its work-hardening capacity when the sectional area is reduced only 25 percent.) A notch in a fully annealed single-phase metal after repeated stress at the fatigue limit, therefore, is essentially a notch in metal that has been somewhat work-hardened. Notch sensitivity of a metal whose fatigue limit is far above the elastic limit, consequently, should not be compared with work-hardening capacity of fully annealed metal, but with work-hardening capacity of metal that has been somewhat cold-worked. The degree of cold-working suitable for such comparison, although it cannot be stated exactly, should be at least enough to raise the elastic range to equality with the endurance range (range of stress at the endurance limit).

Fully annealed metals and single-phase alloys, therefore, are not believed to be real exceptions to the rule that notch sensitivity is closely related to percentage strength. The available evidence seems to indicate that notch sensitivity of metals, while it is influenced by elastic hysteresis, depends largely on tensile work-hardening capacity. Further investigation of this subject, however, is needed.

V. INFLUENCE OF TENSILE STRENGTH ON THE FATIGUE LIMIT OF A NOTCHED SPECIMEN

1. THE TWO OPPOSING VARIABLES

It has been shown that percentage decrease in fatigue limit, due to a notch, increases with the tensile strength. The endurance limit of the metal (fatigue limit obtained with smooth specimens), however, also increases with the tensile strength. The nominal fatigue limit of a notched specimen, therefore, is influenced by 2 opposing variables, each increasing with the tensile strength. The resultant of these 2 variables determines how much of the advantage due to superior strength is offset by disadvantage due to higher notch sensitivity.

2. INFLUENCE OF TENSILE STRENGTH ON THE FATIGUE LIMIT OF NOTCHED SPECIMENS OF STEEL (NOT COLD-WORKED)

The variation of endurance limit with tensile strength has received consideration by a number of investigators. A composite curve for steels, based on a large amount of data assembled from various sources was published by Gillett and Mack on page 147 of their book (3). This curve has been reproduced in figure 13. For steels with tensile strength less than about 200,000 lb/in.^{2}, as indicated by the curve, the endurance limit is approximately proportional to the tensile strength. With increase in tensile strength above 200,000 lb, the ratio of endurance limit to tensile strength (endurance ratio) de-

creases. As this decrease probably is due in part to increasing internal stress, special treatment aimed at reduction of internal stress probably would raise the endurance ratio, for many of these hard steels, above the values represented by the uppermost curve. Nevertheless, this curve probably gives a correct indication of the results obtainable in present commercial practice.

By making use of this curve and any of the percentage-damage curves, in figures 3, 4, 7, 8, and 9, other curves may be constructed to represent the influence of tensile strength on the fatigue limit. Three such curves have been drawn in figure 13.

The curve representing 2 days' corrosion illustrates the influence of a shallow notch. With this notch, the advantage of superior tensile strength evidently is diminished slightly. The effect of a sharper notch is illustrated by the curve representing 10 days' corrosion. With this notch, much of the advantage of superior strength is lost, especially for a range of tensile strength above about 200,000 lb; for ranges of lower strength, considerable advantage of superior strength still remains. The effect of a still sharper notch is illustrated by the curve (derived from a curve in fig. 7) representing the influence of a notch with $\frac{d}{r}$ ratio 28.4. This notch eliminates practically all advantage of increase in tensile strength above about 100,000 lb; for ranges of lower strength, some advantage of superior strength still remains. With a much sharper notch, such as a crack or sharp internal flaw, all advantage of superior strength probably would disappear.

The lowest curve of figure 13, as drawn, slopes downward with increase of tensile strength above about 200,000 lb. Such downward slope appears possible on account of the decrease in endurance ratio with increasing tensile strength, as indicated by the curvature of the uppermost curve. If the endurance ratio did not so decrease, the fatigue limit of even a sharply notched specimen probably would not decrease with increasing tensile strength. Such decrease in fatigue limit, if it exists, probably is slight.

3. INFLUENCE OF WORK-HARDENING ON THE FATIGUE LIMIT OF A NOTCHED SPECIMEN

For some metals, such as copper and nickel-copper alloys (18,19,20), work-hardening increases the endurance limit about in proportion to the increase in tensile strength, provided the work-hardening does not exceed a certain degree, which varies with the metal. Beyond this degree, the endurance ratio decreases. For other alloys, such as copper-tin and copper-zinc alloys (18,19,20), the endurance ratio decreases with even moderate cold working.

The influence of work-hardening on the fatigue limit of a notched specimen evidently would depend on the influence of work-hardening on the endurance ratio. If the endurance ratio is approximately constant throughout a considerable range of work-hardening, the curves of variation of the fatigue limit with tensile strength would be similar in form to the curves for notched specimens in figure 13, with the exception of the descending portion at the right of the lowest curve. With increasing sharpness of notch, the curves (as they extend to the right) would approach a horizontal direction, but would not

descend. Superior strength would lose more or less of its advantage but would not be a disadvantage.

If the endurance ratio decreases with work-hardening, the loss of advantage of superior strength (caused by a notch) is greater than if the endurance ratio remains constant. The fatigue limit of a sharply notched specimen may even be less for severely cold-worked than for fully annealed material.

Moderately cold-worked metals with a notch of the form shown in figure 7, however, were found by one of the authors (21) to have about the same fatigue limit as the corresponding fully annealed metals.

4. INFLUENCE OF HEAT TREATMENT ON THE FATIGUE LIMIT OF NOTCHED SPECIMENS OF NONFERROUS ALLOYS

For some nonferrous alloys, increase of the endurance limit by heat-treatment is less than proportional to the increase in tensile strength. The loss of advantage of superior strength due to a notch, therefore, probably is greater for these alloys than for steels, with the possible exception of very hard steels. The fatigue limit of a sharply notched specimen may possibly be lower when such a nonferrous alloy is heat treated than when it is fully annealed. In use of such alloys, therefore, it is especially important to avoid sharp notches and other abrupt changes of section.

5. INFLUENCE OF INTERNAL FLAWS

Internal flaws lower the apparent notch sensitivity, as the effect of such flaws on the fatigue limit is relatively greater for smooth than for notched specimens. The foregoing discussion of the influence of notches, therefore, is based on the assumption that the metal does not contain internal flaws of size comparable with that of the notch. It does not apply to a metal such as cast iron, of which the continuity is broken by particles of graphite.

The ratio between endurance limit and tensile strength of smooth specimens is greatly influenced by internal flaws. Such flaws in metal hardened by either heat treatment or cold work cause the endurance ratio to be less for hardened than for annealed metal. A line representing smooth specimens of metal with internal flaws, therefore, would be more or less curved like the lines in figure 13 representing outwardly notched specimens. Internal flaws thus may be the chief cause of the curvilinear relationship between endurance limit and tensile strength of some commercial alloys. An external notch in such metal evidently would remove less of the advantage of superior strength than if the curvilinear relationship were due to inherent properties of the metal.

A general résumé of technical information on spring materials is being prepared by cooperation of American Steel Foundries and the National Bureau of Standards, for eventual publication by the special research committee on mechanical springs, American Society of Mechanical Engineers. The present paper considers one phase of the subject. This paper was presented orally (by Dr. H. J. Gough of the National Physical Laboratory) at the Fourth International Congress for Applied Mechanics, Cambridge, England, July 9, 1934, and was published in abstract form by the Congress under the title "Relationship Between Notch Sensitivity and Other Properties of Metals."

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Acknowledgment is due to J. R. Townsend, chairman, of the research committee for his cooperation and encouragement. Acknowledgment is also due to R. D. Brizzolara, chief engineer, and to A. H. Peycke, manager, brake and spring departments, American Steel Foundries, for their continual encouragement and cooperation.

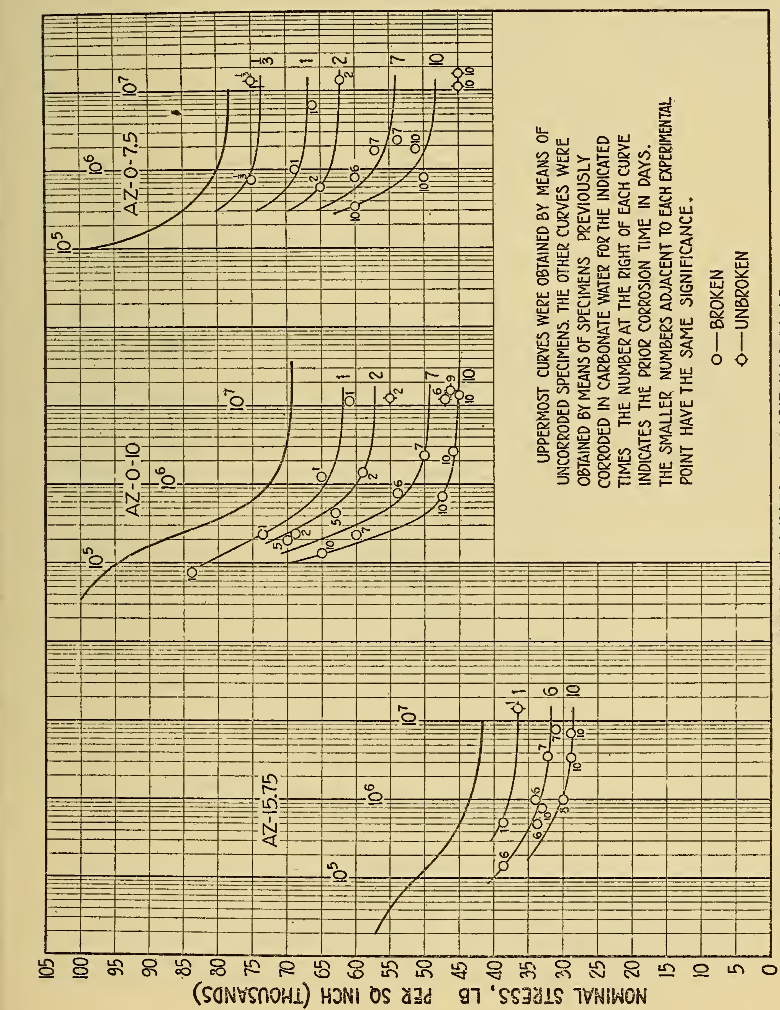

FIGURE 1.—*Influence of prior stressless corrosion of steels on the position of the stress-cycle graph.*

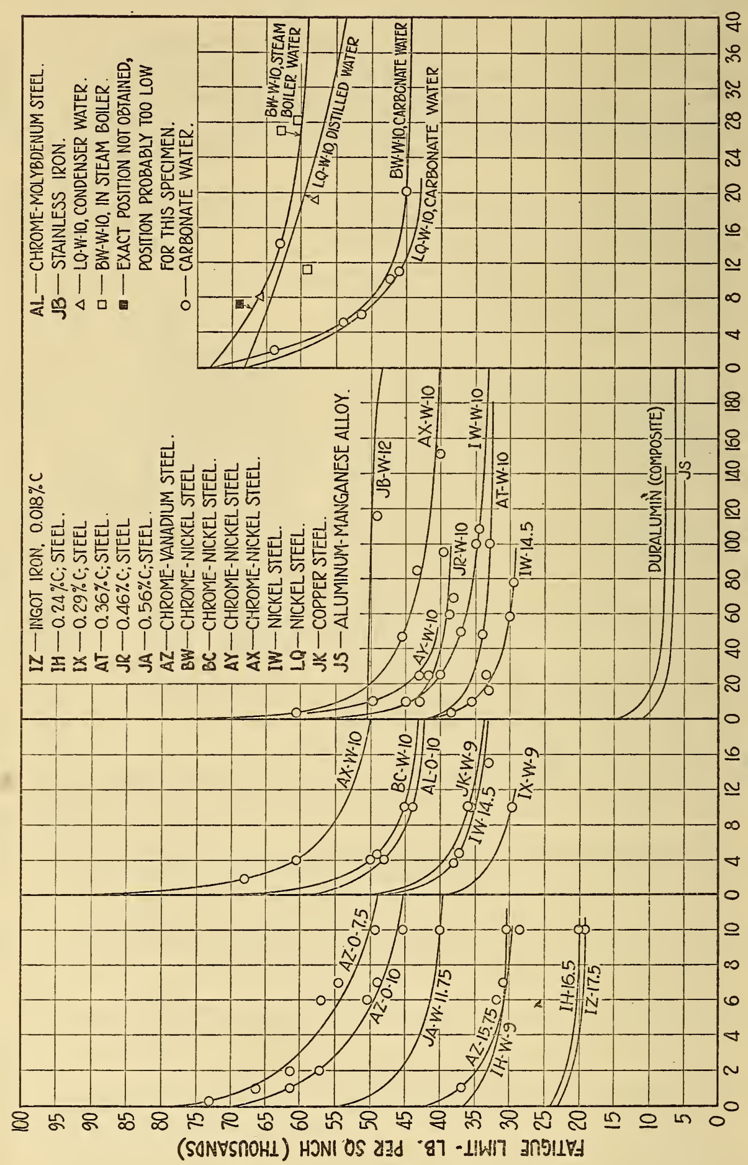

FIGURE 2.—*Influence of duration of prior stressless corrosion on the fatigue limit.*

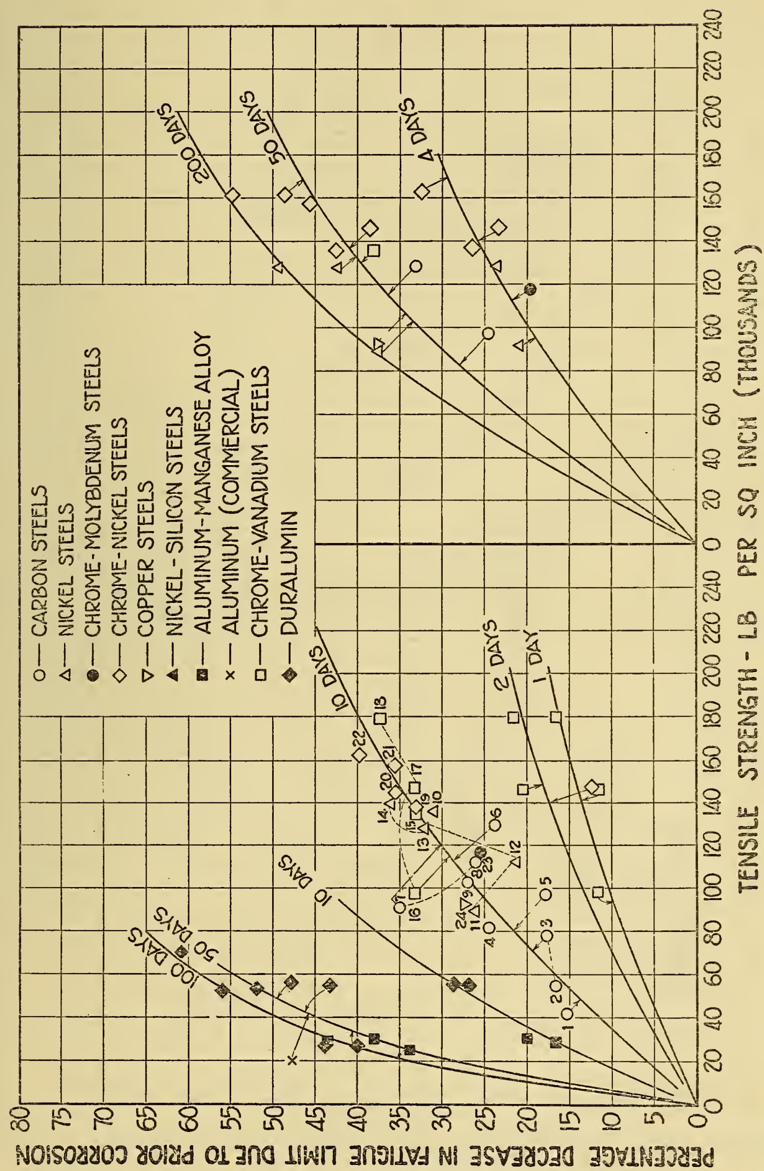

FIGURE 3.—*Relation between tensile strength and percentage decrease in fatigue limit of steels due to stressless corrosion.*

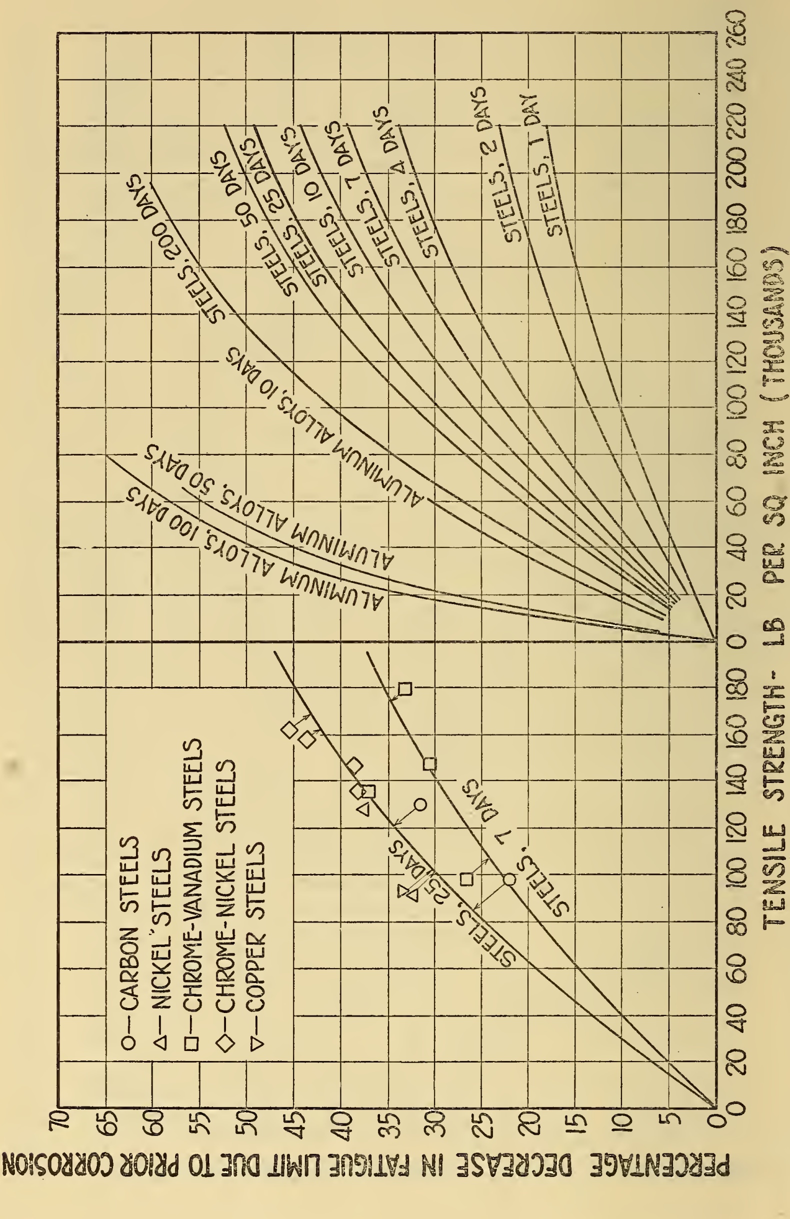

FIGURE 4.—*Relation between tensile strength and the percentage decrease in fatigue limit of steels due to stressless corrosion.*

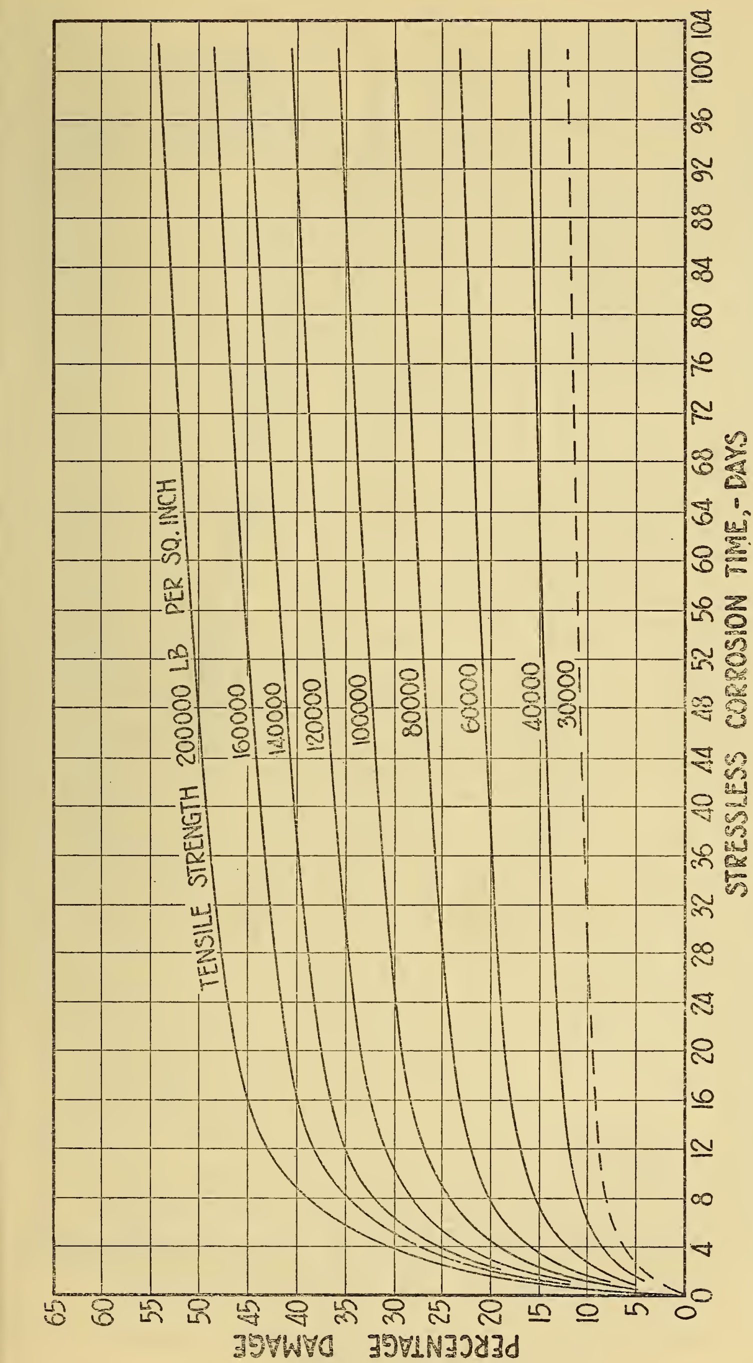

FIGURE 5.—*Relation between stressless-corrosion time and the percentage decrease in fatigue limit of carbon steels and ordinary alloy steels.*

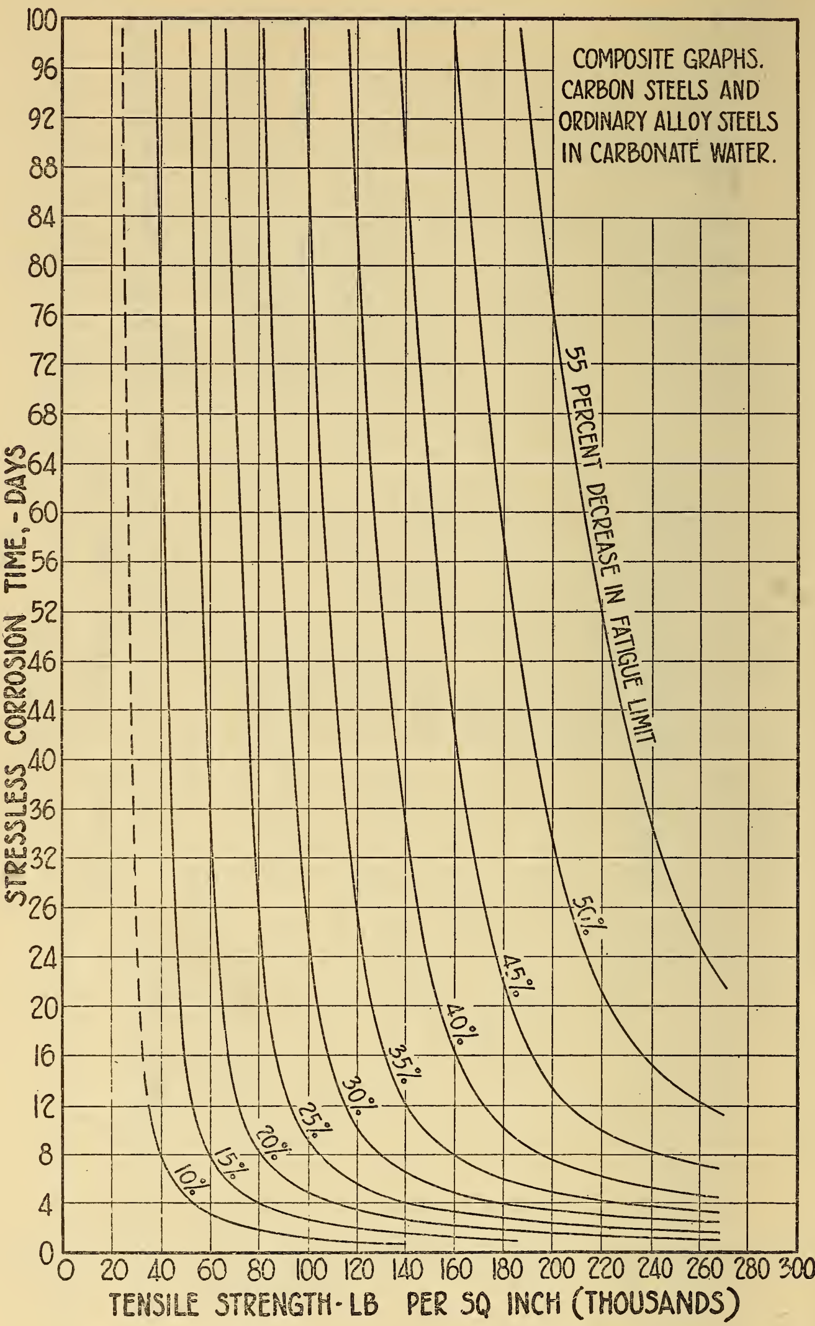

FIGURE 6.—*Relation between tensile strength and stressless-corrosion time, for various percentages of damage.*

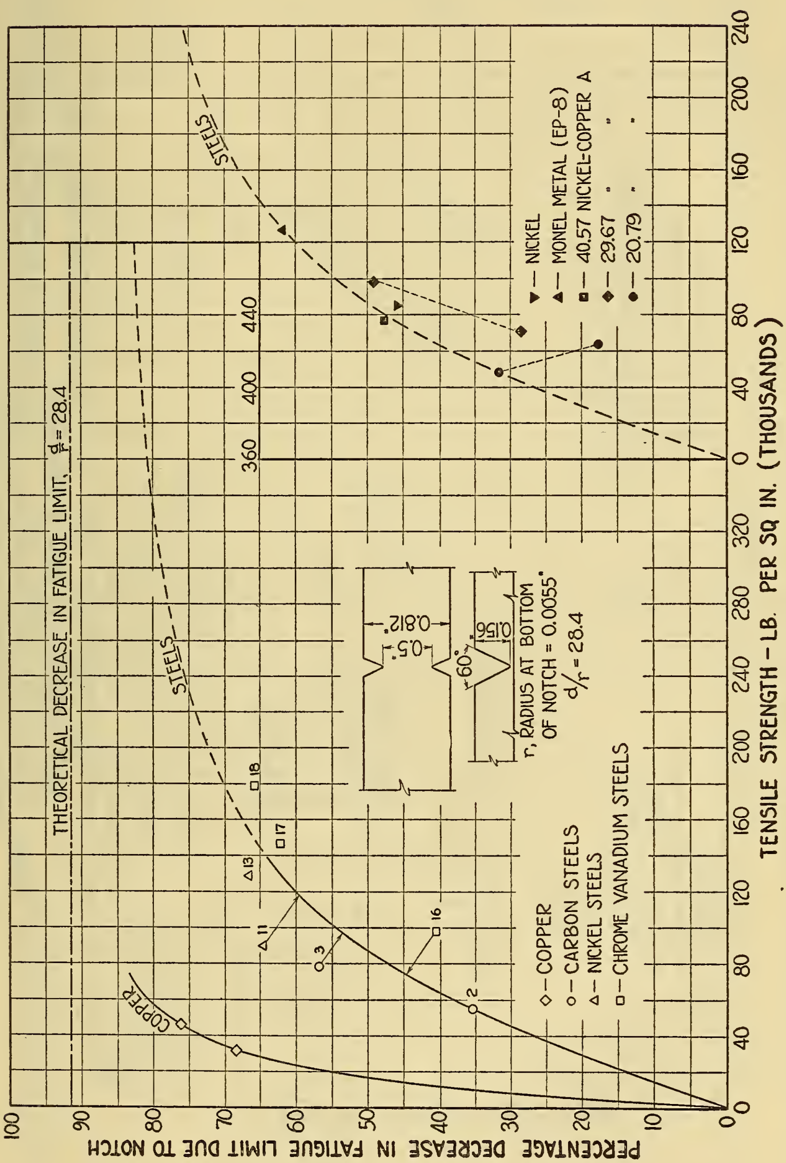

FIGURE 7.—*Relation between tensile strength and the percentage decrease in fatigue limit due to a mechanically formed notch.*

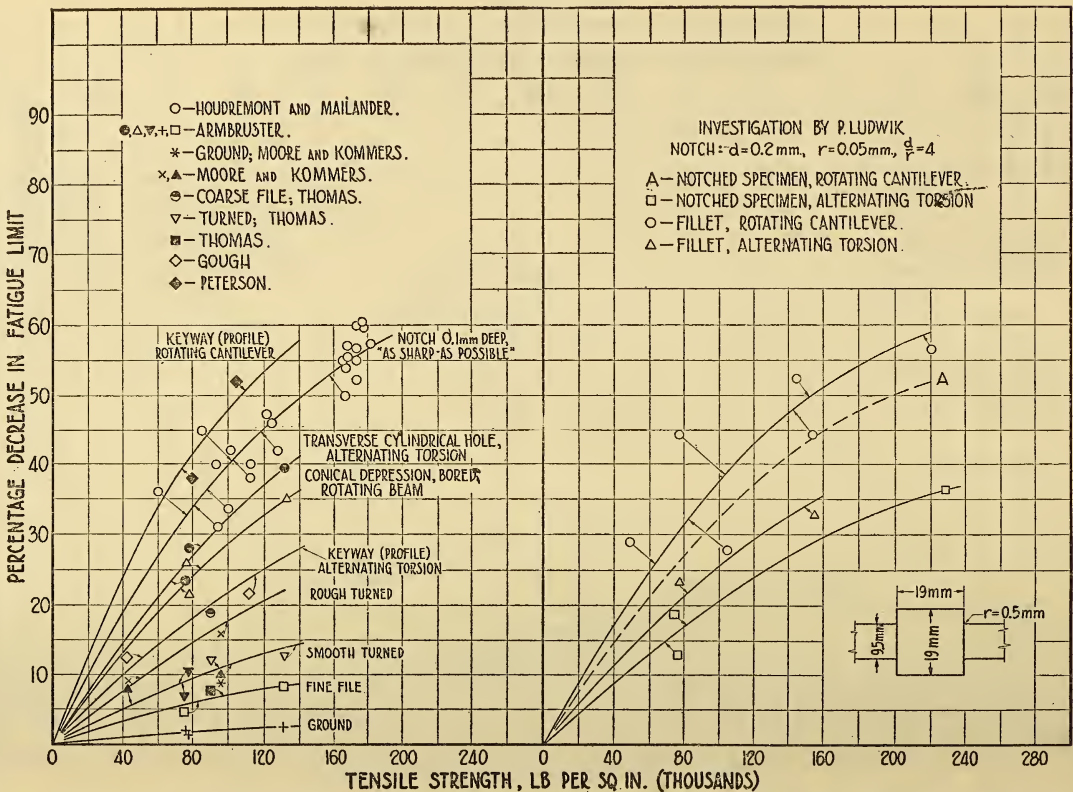

FIGURE 8.—*Relation between tensile strength and the percentage damage due to grooves, holes, fillets, keyways, depressions, and surface roughness.*

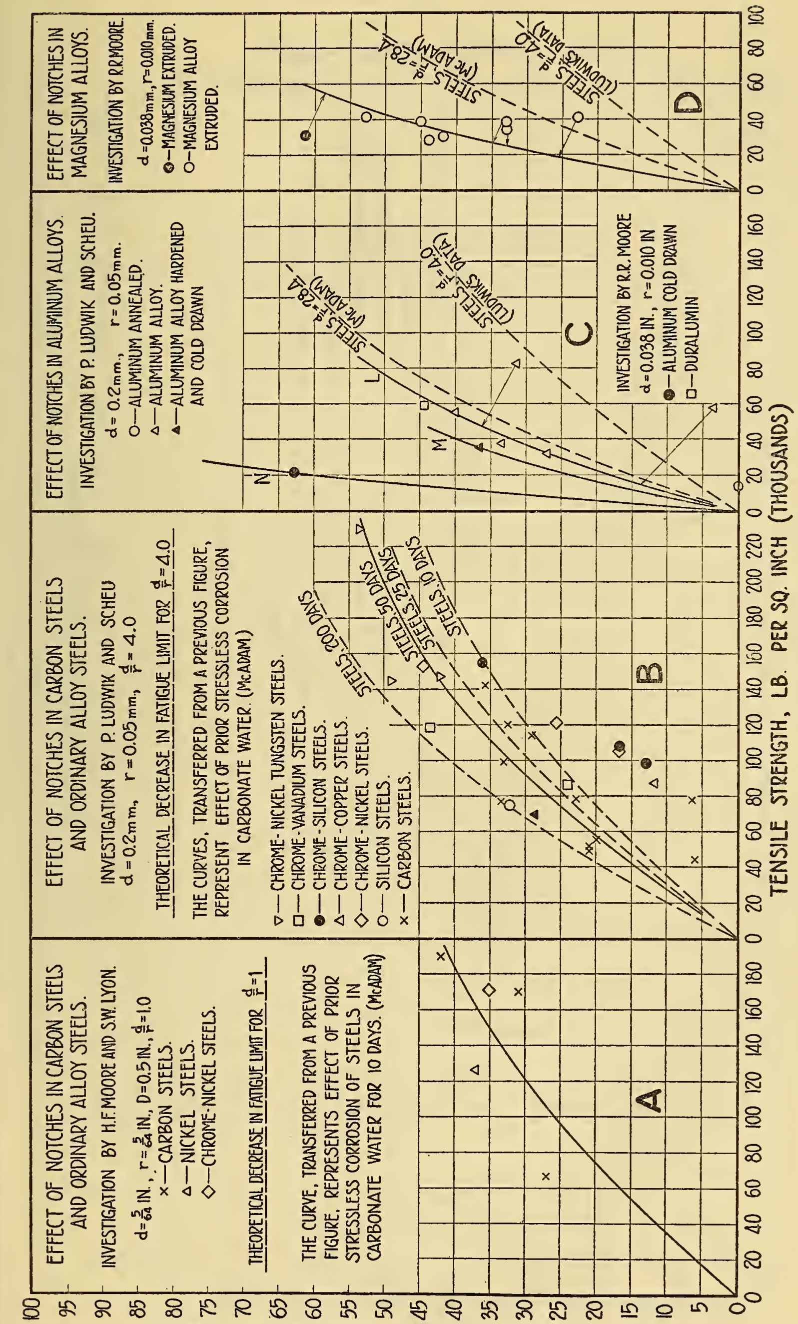

FIGURE 9.—Relation between tensile strength and percentage damage due to notches in various metals and alloys.

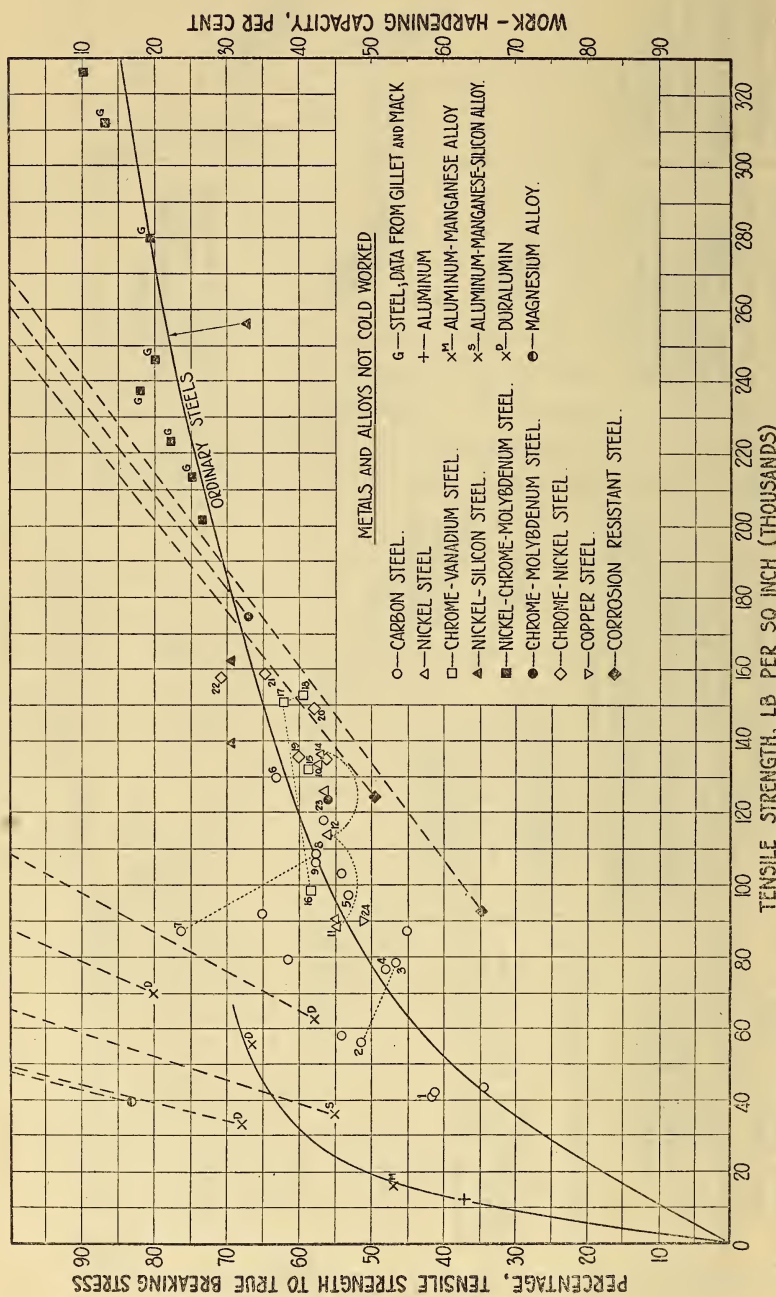

FIGURE 10.—*Relation between tensile strength and tensile work-hardening capacity, as influenced by composition and heat treatment.*

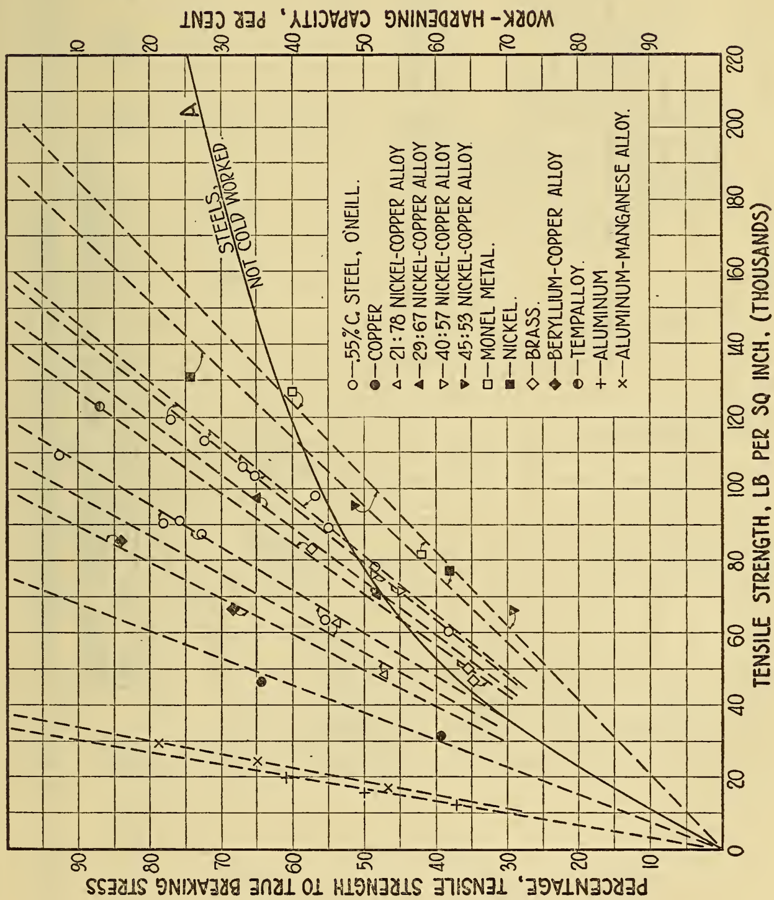

FIGURE 11.—*Relation between tensile strength and tensile work-hardening capacity, as influenced by cold working.*

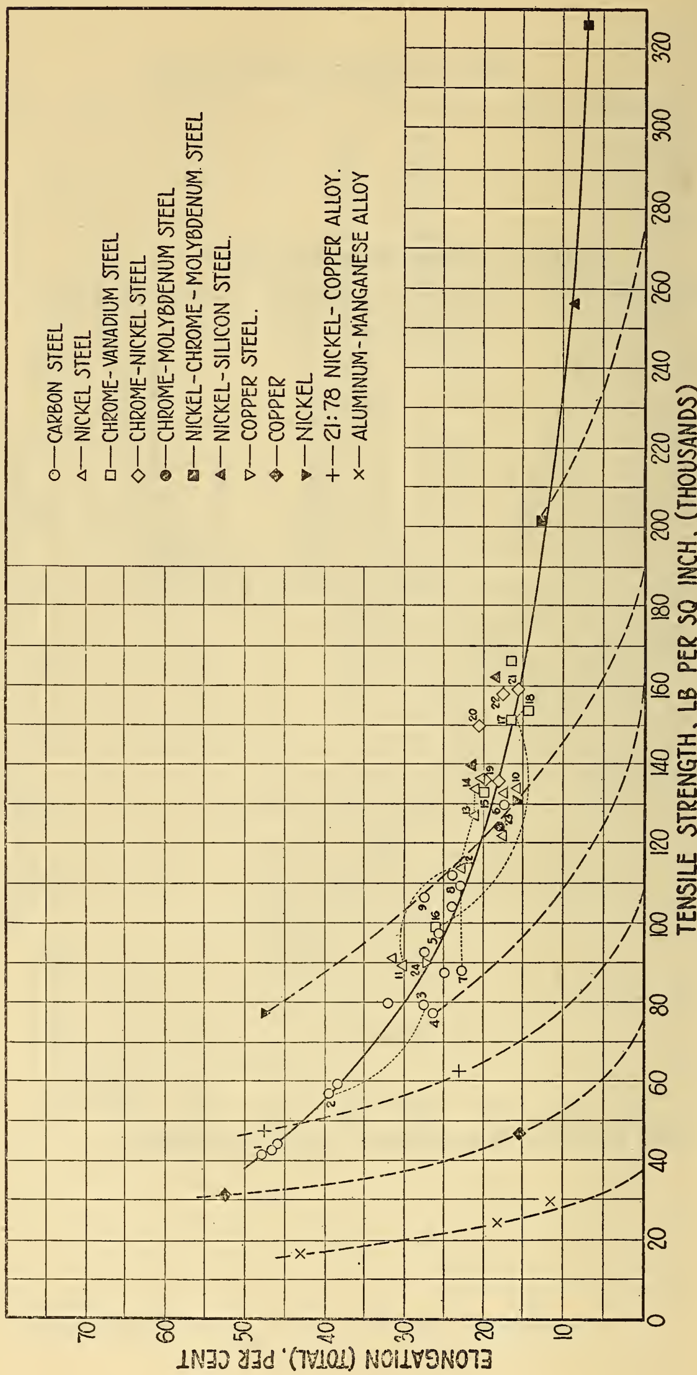

FIGURE 12.—*Relation between tensile strength and total tensile elongation* (percent in 2 inches).

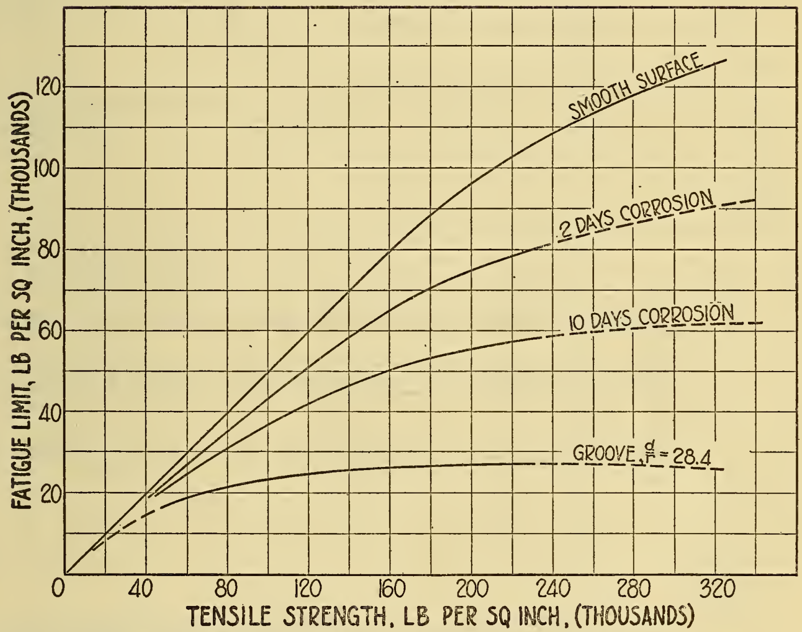

Figure 13.—*Loss of advantage of superior strength due to notches.*

TABLE 1.—*Chemical composition*

Material [a]	Composition (percent)													
	Designation	C	Mn	Si	Cv	V	Ni	Mo	Cu	Zn	Sn	Al	Mn	Fe
Ingot iron	EK	0.032	0.025	0.003										
Do	IZ	.018	.016	.002										
0.24 percent C Steel	EL	.24	.4	.023										
Do	IH	.24	.57	.006										
0.26 percent C steel	EN	.26	.57	.06										
0.29 percent C steel	IX	.28	.54	.01										
0.36 percent C steel	AT	.36	.55	.3	0.014			0.06						
Do	AG	.36	.61	.019										
0.46 percent C steel	JR	.46	.65	.016										
0.49 percent C steel	AE	.49	.41	.23										
0.56 percent C steel	JA	.56	.67	.12										
1.09 percent C steel	EM	1.09	.33	.28										
3½ percent Ni steel	EJ	.32	.6	.21			3.47							
Do	LQ [b]													
3.7 percent Ni steel	IW	.28	.5	.19	.26		3.7							
5 percent Ni steel	CA	.52	.41	.32			5.37							
Chromium-vanadium steel	AU	.34	.71	.21	1.05	0.17								
Do	AZ	.46	.69	.24	.88	.14								
Do	AR	.50	.70		.99	.16								
Chromium-nickel steel	BC	.28	.69	.21	.73		1.51							
Do	AH	.39	.69	.17	.82		1.67							
Do	BW	.39	.57	.19	.92		1.83							
Do	AY	.43	.60	.21	.95		2.16							
Do	AX	.36	.48	.22	1.55		3.26							
Chromium-molybdenum steel	AL	.33	.71	.13	.95			.15						
Nickel-chromium-molybdenum steel	KO	.49	.64	.23	.94		1.93	.37						
Nickel-silicon steel	HG	.47	.87	1.58	.32		3.11							
Copper steel	IK	.27	.47	.01					0.82					
Stainless iron	GR	.12	.40	.18	12.67		.45		.05					
Do	GN	.13	.05	.22	13.35		.08		.45					
Do	GO	.08	.18	.23	12.20		.18		.13					
Do	FH	.11	.04	.10	11.84		.07		.94					
Stainless steel	FJ	.33	.08	.09	11.54		.08		.84					
Do	GS	.38	.26	.20	14.50		.23		.07					
Corrosion-resistant steel	EX	.80	.86	1.70	19.01		12.19		.05					
Do	EW	.38	.71	2.36	15.95		15.88		.08					
Do	EV	.39	.66	.144	17.71		25.25		.012					
Do	EU	.70	.72	3.08	17.32		25.81		.05					
Do	ES	.24	.80	1.65	5.42		22.90		.78					
Do	ET	.45	.49	1.39	8.38		28.20		.67					
Copper, electrolytic, HR	EE													0.004
Copper, electrolytic, CW	HU													.008

21:78 nickel-copper alloy, CW	HE	.031	.29	.005	----	----	21.24	----	77.92	----	----	----	----	.51
29:67 nickel-copper alloy, CR	HZ	.040	1.35	.002	----	----	28.66	----	67.11	----	----	----	----	2.82
40:57 nickel-copper alloy, HR	EH	.160	1.77	.06	----	----	40.29	----	56.63	----	----	----	----	1.09
Constantan, CR	HP	.04	1.03	.02	----	----	45.00	----	53.54	----	----	----	----	.38
Monel metal, CR	EP	.159	.95	.05	----	----	67.51	----	29.54	----	None	----	----	1.76
Nickel, CR	EO	.098	.03	.09	----	----	98.96	----	.17	----	----	----	----	.57
Nickel-copper-zinc alloy, CD	CG	----	----	----	----	----	10.89	----	60.08	29.05	----	----	----	----
Ambrac, HR	CD	----	.75	----	----	----	19.75	----	74.01	5.17	----	----	----	----
Copper-nickel-tin alloy, CD	CF	----	----	----	----	----	29.08	----	69.82	----	.95	----	----	----
92:8 copper-tin alloy, CD	EDA	----	----	----	----	----	----	----	91.78	----	8.20	----	----	.07
90:10 copper-tin alloy, CD	EC-12	----	----	----	----	----	.13	----	89.41	----	10.49	----	----	.07
Do	ECA	----	----	----	----	----	----	----	----	----	----	----	----	----
71:28:1 copper-zinc-tin alloy	MA	----	None	.003	----	----	----	----	70.64	28.18	1.17	----	----	.01
65:35 copper-zinc alloy, CD	EG	----	----	----	----	----	----	----	64.95	35.06	----	----	----	.04
Aluminum bronze	KE	----	----	----	----	----	----	----	90.39	----	----	10.00	----	.17
Do	BJB	----	----	----	----	----	----	----	90.52	----	----	10.01	----	.002
Copper-nickel-silicon alloy	KBA	----	----	.82	----	----	3.27	----	95.96	----	----	----	----	.087
Aluminum, A	DR	----	.005	.22	----	----	----	----	.12	----	----	99.35	----	.30
Aluminum, ½ HT	DRA	----	.005	.22	----	----	----	----	.12	----	----	99.35	----	.30
Aluminum, HT	DRB	----	.005	.22	----	----	----	----	.12	----	----	99.35	----	.30
Alluminum-manganese alloy, A	DS	----	1.22	.35	----	----	----	----	.16	----	----	97.98	----	.29
Aluminum-manganese alloy, ½ HT	DSA	----	1.22	.35	----	----	----	----	.16	----	----	97.98	----	.29
Aluminum-manganese alloy, HT	DSB	----	1.22	.35	----	----	----	----	.16	----	----	97.98	----	.29
Do	JS	----	1.35	.16	----	----	----	----	.15	----	----	97.76	----	.59
Duralumin, T	KI	----	.72	.36	----	----	----	----	4.37	----	----	93.31	.55	.69
Do	GU	----	.55	.29	----	----	----	----	4.10	----	----	93.86	.63	.57
Do	LG	----	.58	.40	----	----	----	----	4.04	----	----	93.95	.35	.68
Duralumin	DU	----	.60	.37	----	----	----	----	4.18	----	----	93.89	.92	.54
Duralumin, T	DUA	----	.60	.37	----	----	----	----	4.18	----	----	93.89	.92	.54
Do	GT	----	.50	1.02	----	----	----	----	3.72	----	----	94.06	.28	.42
Do	KA	----	.63	.21	----	----	----	----	4.26	----	----	93.60	.63	.67
Do	JU	----	.52	.18	----	----	----	----	4.14	----	----	93.37	.62	1.17
Aluminum-copper alloy	DVA	----	.82	.82	----	----	----	----	4.55	----	----	Rem.	----	.56
Aluminum-magnesium-silicon alloy	DTA	----	.006	.56	----	----	----	----	.15	----	----	98.19	.55	.54
Do	DTB	----	.006	.56	----	----	----	----	.15	----	----	98.19	.55	.54
Magnesium-aluminum alloy	CN	----	.002	.01	----	----	----	----	----	None	None	4.40	95.91	.15

[a] HR, hot rolled; CW, cold worked; CR, cold rolled; CD, cold drawn; A, annealed; T, tempered; HT, hard temper; ½ HT, half-hard temper.
[b] About the same in composition as IW.

TABLE 2.—*Details of mechanical and thermal treatment*

Comparison number	Material [a]	Designation	Heat treatment					
			Temperature	Time held	Cooled in	Temperature	Time held	Cooled in
			° F	*Min*		*° F*	*Min*	
	Ingot iron	EK-17.5	1,750	30	Furnace			
	do	EK-W-7	1,750	45	Water	700	120	Furnace.
1	do	IZ-17.5	1,750	45	Furnace			
	0.24-percent C steel	EL-16.5	1,650	60	do			
2	do	IH-16.5	1,650	60	do			
3	do	IH-W-9	1,650	60	Water	900	120	Air.
	0.26-percent C steel	EN-W-9	1,650	60	do	900	120	Furnace.
4	0.29-percent C steel	IX-W-9	1,650	60	do	900	120	Air.
5	0.36-percent C steel	AT-W-10	1,550	60	do	1,000	120	Furnace.
	do	AG-15.5	1,550	60	Furnace			
	do	AG-W-9	1,550	60	Water	900	120	Do.
6	0.46-percent C steel	JR-W-10	1,500	60	do	1,000	120	Do.
	0.49-percent C steel	AE						
	do	AE-W-10	1,500	60	Water	1,000	120	Do.
7	0.56-percent C steel	JA-15	1,500	60	Furnace			
8	do	JA-W-11.75	1,500	60	Water	1,175	60	Do.
9	1.09-percent C steel	EM-14.75	1,475	60	Furnace			
	3½-percent Ni steel	EJ-14.5	1,675	60	Air	1,450	60	Do.
	do	EJ-W-10 [b]	1,450	60	Water	1,000	120	Do.
10	do	LQ-W-10	1,450	60	do	1,000	120	Do.
11	3.7-percent Ni steel	IW-14.5	1,450	60	Furnace			
12	do	IW-W-11 [c]	1,450	60	Water	1,100	120	Do.
13	do	IW-W-10 [c]	1,450	60	do	1,000	120	Do.
14	do	IW-W-9 [c]	1,450	60	do	900	120	Do.
	5-percent Ni steel	CA-14.25	1,425	60	Furnace			
15	Chromium-vanadium steel	AU-O-10 [d]	1,575	60	Oil	1,000	60	Do.
16	do	AZ-15.75 [d]	1,575	60	Furnace	Previously heated to 1,700° F. for 60 min. cooled in air.		
17	do	AZ-O-10 [d]	1,575	60	Oil	1,000	60	Furnace.
18	do	AZ-O-7.5 [d]	1,575	60	do	750	60	Do.
	do	AR	1,575	60	do	1,000	60	Do.
19	Chromium-nickel steel	BC-W-10	1,550	60	Water	1,000	120	Do.
	do	AH	Heat treated airplane crank shaft material.					
20	do	BW-W-10	1,550	60	Water	1,000	120	Furnace.
21	do	AY-W-10	1,550	60	do	1,000	120	Do.
22	do	AX-W-10	1,550	60	do	1,000	120	Do.
23	Chromium-molybdenum steel.	AL-O-10	1,575	60	Oil	1,000	60	Do.
	Nickel-chromium-molybdenum steel.	KO-O-8	1,600	60	do	800	60	Air.
	do	KO-O-3.5	1,600	60	do	350	60	Do.
	Nickel-silicon steel	HG-14.75	1,475	60	Furnace			
	do	HG-O-10	1,500	60	Oil	1,000	60	Do.
	do	HG-O-7.5	1,500	60	do	750	60	Do.
24	Copper steel	JK-W-9	1,600	60	Water	900	120	Furnace.
	Stainless iron	GR	Heat treated by manufacturer.					
	do	GN-W-12	1,800	90	Water	1,200	120	Air.
	do	GO-18	1,800	120	Furnace			
	do	GO-W-12	1,800	60	Water	1,200	120	
	do	FH-16	1,600	120	Furnace			
	Stainless steel	FJ-17	1,700	120	do			
	do	GS-17	1,700	120	do			
	do	GS-O-12	1,800	60	Oil	1,200	120	Do.
	do	GS-O-10.75	1,800	60	do	1,075	120	Do.
	Corrosion-resistant steel	EX						
	do	EW						
	do	EV						
	do	EU						
	do	ES						
	do	ET						
	Copper, electrolytic, HR	EE-12	1,200	60	Furnace			
	Copper, electrolytic, CW	HU-2.5	250	180	do			
	21:78 nickel-copper alloy, CW.	HE-14	1,400	60	do			
	do	HE-4	400	180	do			
	29:67 nickel-copper alloy, CR.	HZ-14.5	1,450	60	do			

[a] HR, hot rolled; CW, cold worked; CR, cold rolled; CD, cold drawn; A, annealed; T, tempered; ½ HT, half hard temper; HT, hard temper; when no heat treatment is listed, material was tested as received.
[b] Previously heated to 1675° F for 30 min, cooled in air.
[c] Previously heated to 1675° F for 60 min, cooled in air.
[d] Previously heated to 1700° F for 60 min, cooled in air.

TABLE 2.—*Details of mechanical and thermal treatment*—Continued

Comparison number	Material	Designation	Heat treatment: Temperature	Heat treatment: Time held	Heat treatment: Cooled in	Heat treatment: Temperature	Heat treatment: Time held	Heat treatment: Cooled in
			° F	*Min*		*° F*	*Min*	
	29:67 nickel-copper alloy, CR.	HZ-8.5	850	180	Furnace			
	40:57 nickel-copper alloy, HR.	EH-14	1,400	60	do			
	do	EH						
	Constantan, CR	HP-12	1,200	60	Furnace			
	do	HP-7.5	750	180	do			
	Monel metal, CR	EP-14	1,400	60	do			
	do	EP-8	800	180	do			
	Nickel, CR	EO-14	1,400	60	do			
	do	EO-6	600	120	do			
	Nickel silver, CD	CG						
	92:8 copper-tin alloy	EDA-12	1,200	60	Furnace			
	92:8 copper-tin alloy, CD	EDA						
	90:10 copper-tin alloy, CR	EC-12	1,200	60	Furnace			
	do	ECA						
	71:28 copper-zinc alloy	MA						
	65:35 copper-zinc alloy, CD.	EG-12	1,200	60	Air			
	do	EG-4.5	450	60	do			
	Aluminum bronze	KE						
	do	KE-6	600	180	Furnace			
	do	BJB-11						
	Copper-nickel-silicon alloy	KBA-8	{Hard drawn rods heat treated. Final heat treatment, 2 hours at 797° F.					
	Beryllium copper, CR	MT-14.25-W	1,425		Water	Previously cold rolled 25 percent, as received.		
	do	MT-4.5	T.450	Previously cold rolled 25 percent, as received.				
	Aluminum, A	DR						
	Aluminum, ½ HT	DRA						
	Aluminum, HT	DRB						
	Aluminum-manganese alloy, A.	DS						
	Aluminum-manganese alloy, ½ HT.	DSA						
	Aluminum-manganese alloy, HT.	DSB						
	do	JS	Heat treated by manufacturer.					
	Duralumin, T	KI	Do.					
	do	GD	Do.					
	do	LG	Do.					
	Duralumin	DU	Annealed by manufacturer.					
	Duralumin, T	DUA	Heat treated by manufacturer.					
	do	GT	Do.					
	Duralumin	KA	Do.					
	do	JU	Do.					
	Aluminum-copper alloy, ½ HT.	DVA	Do.					
	Aluminum-manganese-silicon alloy.	DTA	Do.					
	do	DTB	Do.					
	Magnesium-aluminum alloy.	CN						

TABLE 3.—*Physical properties*

NOTES

"*Proof stress*" is the stress that, after release of load, will cause permanent elongation of 0.0001 in. per inch length. "*Elastic limit*" is the highest stress that, after release of load, will cause no appreciable permanent elongation. "*Proportional limit*" is the highest stress that will not cause appreciable departure from a linear stress-strain relationship. (The smallest divisions of the extensometer scale were 0.0001, but estimate could be made to 0.00002 in. The extensometer was of a type that permitted accurate determination of permanent set.) "*True breaking stress*" is the actual breaking load divided by the reduced area at fracture.

Comparison no.	Material	Condition [a]	Designation	Tensile strength (TS) [b]	Johnson's limit [b]	Proof stress (PS) [b]	Elastic limit [b]	Proportional limit [b]	Elongation in 2 inches [b]	Reduction of area [b]	Endurance limit	True stress at maximum load	True breaking stress (TBS)	Elongation at maximum load	Percentage ratio PS to TBS	Percentage ratio TS to TBS
				lb/sq in.	*lb/sq in.*	*lb/sq in.*	*lb/sq in.*	*lb/sq in.*	*Percent*	*Percent*	*lb/sq in.*	*lb/sq in.*	*lb/sq in.*	*Percent*	*Percent*	*Percent*
------	Ingot iron	A	EK-17.5	42, 500	15, 000	16, 000	14, 000	14, 000	46. 5	71. 5	21, 000	49, 700	105, 000	16. 95	15. 5	41. 25
------	do	WQ and T	EK-W-7	44, 000	22, 000	22, 500	21, 000	20, 000	46. 0	75. 0	24, 000	52, 400	128, 000	19. 1	17. 6	34. 35
1	do	A	IZ-17.5	41, 500	17, 000	17, 000	17, 000	16, 000	48. 0	73. 6	24, 000	52, 500	100, 000	26. 5	17. 0	41. 50
------	0.24 percent C steel	A	EL-16.5	50, 300	32, 000	33, 000	32, 000	31, 000	58. 5	58. 5	27, 000	71, 000	109, 000	19. 78	30. 5	54. 2
2	do	A	IH-16.5	56, 700	40, 000	40, 000	28, 000	26, 000	39. 5	61. 3	24, 000	67, 200	110, 000	17. 82	36. 35	51. 5
3	do	WQ and T	IH-W-9	79, 000	60, 000	58, 000	57, 000	50, 000	27. 5	67. 9	37, 000	89, 600	169, 700	12. 6	34. 2	46. 5
------	0.26 percent C steel	WQ and T	EN-W-9	87, 500	60, 000	60, 000	55, 000	50, 000	25. 0	62. 5	39, 000	97, 800	195, 400	11. 74	31. 0	45. 2
4	0.29 percent C steel	WQ and T	IX-W-9	77, 000	52, 000	52, 000	50, 000	50, 000	26. 5	66. 9	38, 500	86, 200	159, 800	11. 96	32. 5	48. 1
5	0.36 percent C steel	WQ and T	AT-W-10	97, 500	71, 000	71, 500	70, 000	70, 000	25. 5	60. 4	42, 000	108, 800	183, 500	11. 73	39. 0	53. 25
------	do	A	AG-15.5	79, 500	48, 000	47, 500	47, 000	35, 000	32. 0	49. 0	--------	92, 000	129, 000	15. 65	36. 8	61. 6
------	do	WQ and T	AG-W-9	103, 500	75, 000	75, 500	75, 000	60, 000	24. 0	59. 5	--------	113, 900	191, 000	10. 0	39. 5	54. 2
6	0.46 percent C steel	WQ and T	JR-W-10	129, 800	100, 000	101, 400	99, 500	92, 300	17. 5	51. 9	59, 000	138, 300	205, 400	6. 5	49. 5	63. 2
------	0.49 percent C steel	AR	AE	92, 300	57, 000	59, 000	57, 000	--------	27. 5	43. 5	--------	108, 400	141, 500	17. 16	41. 7	65. 2
------	do	WQ and T	AE-W-10	111, 800	76, 000	77, 000	76, 000	63, 000	24. 0	56. 0	53, 000	122, 500	197, 600	10. 43	38. 95	56. 6
7	0.56 percent C steel	A	JA-15	87, 400	36, 500	37, 000	36, 000	32, 500	23. 0	29. 2	43, 000	100, 600	114, 500	15. 22	32. 3	76. 3
8	do	WQ and T	JA-W-11.75	109, 400	--------	--------	--------	--------	23. 0	58. 5	54, 000	119, 300	189, 700	9. 13	-------	57. 65
9	1.09 percent C steel	A	EM-14.75	106, 500	63, 000	63, 500	63, 000	53, 000	27. 5	52. 0	42, 500	122, 300	184, 700	14. 48	34. 4	57. 7
------	3½ percent Ni steel	A	EJ-14.5	90, 800	60, 000	61, 000	55, 000	48, 000	31. 5	58. 5	49, 000	96, 700	164, 000	6. 52	37. 2	55. 3
------	do	WQ and T	EJ-W-10	126, 100	107, 000	107, 500	107, 000	80, 000	21. 0	64. 0	69, 000	134, 400	223, 000	6. 96	48. 2	56. 6
10	do	WQ and T	LQ-W-10	133, 700	121, 300	123, 300	121, 300	106, 400	21. 0	63. 8	--------	140, 900	233, 000	5. 44	52. 9	57. 4
11	3.7 percent Ni steel	A	IW-14.5	89, 250	59, 000	60, 000	59, 000	47, 500	30. 0	59. 2	49, 000	114, 400	165, 400	15. 2	36. 3	54. 95
12	do	WQ and T	IW-W-11	114, 000	100, 000	101, 000	97, 500	90, 000	23. 0	64. 4	--------	122, 700	202, 800	7. 61	49. 8	56. 2
13	do		IW-W-10	128, 100	114, 000	114, 600	110, 000	94, 300	20. 6	61. 8	--------	--------	--------	-------	-------	-------
14	do	WQ and T	IW-W-9	136, 000	122, 000	123, 000	115, 000	105, 000	20. 5	61. 5	--------	142, 600	238, 000	4. 78	51. 7	57. 2
------	5 percent Ni steel	A	CA-14.25	122, 000	55, 000	55, 000	45, 000	45, 000	17. 5	24. 0	55, 000	136, 800	155, 200	12. 6	-------	-------
------	do	WQ and T	CA-W-11	133, 000	95, 000	95, 000	80, 000	80, 000	17. 5	39. 0	66, 000	144, 300	185, 000	8. 26	-------	-------
15	Chromium-vanadium steel	OQ and T	AU-O-10	132, 200	111, 000	114, 500	112, 500	100, 000	20. 0	60. 9	68, 500	139, 500	224, 200	5. 48	51. 1	58. 9
16	do	A	AZ-15.75	98, 800	55, 000	55, 000	40, 000	40, 000	26. 0	51. 1	42, 000	114, 400	169, 400	7. 65	32. 45	58. 3
17	do	OQ and T	AZ-O-10	151, 000	122, 500	125, 000	115, 000	90, 000	16. 5	53. 7	69, 000	161, 400	243, 000	6. 82	51. 45	62. 1
18	do	OQ and T	AZ-O-7.5	153, 500	115, 000	117, 500	100, 000	82, 500	14. 5	54. 2	78, 000	162, 500	250, 000	5. 83	45. 6	59. 5
------	do	OQ and T	AR-O-10	166, 500	162, 500	162, 500	150, 000	115, 000	15. 5	51. 1	85, 000	181, 000	305, 000	8. 7	53. 3	54. 6
19	Chromium-nickel steel	WQ and T	BC-W-10	135, 900	119, 100	121, 700	119, 100	111, 500	20. 0	62. 2	68, 000	143, 700	225, 800	5. 22	53. 95	60. 2

	do	AR	AH	135,400	112,500	117,000	107,500	90,000	18.0	54.9	66,500	149,500	238,800	10.43	49.0	56.7
20	do	WQ and T	BW-W-10	149,400	132,500	135,000	125,000	120,000	20.5	62.2	75,000	156,500	258,000	4.82	52.35	57.9
21	do	WQ and T	AY-W-10	159,000	143,100	144,200	135,200	103,400	15.5	52.0	76,000	165,000	245,200	4.81	58.8	64.8
22	do	WQ and T	AX-W-10	157,700	141,000	142,000	139,000	115,000	17.5	50.7	89,500	160,500	222,000	5.22	64.0	71.0
23	Chromium-molybdenum steel.	OQ and T	AL-O-10	124,500	94,000	95,000	90,000	78,000	18.0	64.0	58,500	136,100	221,400	9.35	42.9	56.25
	Nickel-Chromium-molybdenum steel.	OQ and T	KO-O-8	201,500	165,000	170,000	165,000	132,500	13.0	43.7		210,700	274,200	4.56	62.0	73.5
	do	OQ and T	KO-O-3.5	326,000	91,900	78,000	65,000	62,800	7.0	11.5		346,000	362,000	6.09	21.5	90.0
	Nickel-silicon steel	A	HG-14.75	139,500	76,000	77,000	70,000	40,000	21.5	43.0	65,000	156,300	200,400	10.78	38.4	69.6
	do	OQ and T	HG-O-10	162,500	115,000	115,000	100,000	90,000	18.5	46.5	89,000	174,800	233,700	7.52	49.2	69.6
	do	OQ and T	HG-O-7.5	256,000	210,000	212,000	204,000	170,000	8.5	47.0	108,000	260,000	377,500	1.5	56.2	67.8
24	Copper steel	WQ and T	JK-W-9	90,000	67,500	67,500	67,500	55,000	27.0	63.6	49,500	101,750	175,400	13.04	38.5	51.3
	18-8 alloy	AR	LZ	92,900	20,100	21,600	15,100	12,600	65.5	74.5		147,350	268,000	58.7	8.1	34.65
	Stainless iron	AR	GR	112,000	79,000	80,500	70,000	65,000	23.5	66.5	53,500	114,000	210,000	5.7	38.3	53.35
	do	WQ and T	GN-W-12	120,200	81,000	82,000	71,000	66,000	23.0	64.5	59,000	127,300	228,400	7.4	35.9	52.6
	do	A	GO-18	61,500	25,000	25,000	19,000	15,000	40.0	69.5	39,000	73,600	132,800	18.7	18.8	46.3
	do	WQ and T	GO-W-12	92,500	60,000	60,000	50,000	45,000	24.0	71.5	49,000	99,000	187,700	6.09	32.0	49.2
	do	A	FH-16	79,800	41,000	42,000	38,000	36,000	32.5	66.0	39,000	90,400	161,900	13.92	25.95	49.3
	Stainless steel	A	FJ-17	96,800	42,000	42,000	38,000	35,000	28.0	61.0	52,000	109,700	183,000	13.5	22.9	52.8
	do	A	GS-17	96,000	43,000	41,000	40,000	40,000	32.0	60.2		109,800	174,600	14.4	23.5	54.9
	do	OQ and T	GS-O-12	112,100	49,000	50,000	43,000	38,000	23.5	56.0	53,500	126,200	208,000	13.7	24.0	53.9
	do	OQ and T	GS-O-10.75	179,000	130,000	123,000	100,000	85,000	11.0	38.5		186,900	234,000	4.35	52.1	76.5
	Corrosion-resistant steel	AR	EX	124,000	45,000	42,500	33,000	30,000	22.5	27.0	65,000	146,000	161,700	17.82	26.3	76.7
	do	AR	EW-17	127,500	53,000	45,000	35,000	35,000	26.0	38.0	64,000					
	do	AR	EV	114,300	50,000	50,000	40,000	30,000	23.0	35.5	54,000	131,500	160,300	15.08	31.2	71.3
	do	AR	EU	110,000	47,500	45,000	37,000	32,000	27.0	38.0	57,000	129,600	161,200	17.82	27.9	68.3
	do	AR	ES	98,800	35,000	38,000	35,000	35,000	33.0	59.0	50,000	117,500	187,800	19.31	24.0	52.6
	do	A	ET-17	113,000	46,000	49,000	45,000	30,000	23.5	37.5		132,800	168,000	17.4	29.1	67.2
	do	AR	ET	124,800	75,000	50,000	40,000	25,000	28.0	59.5	58,000	140,900	251,400	7.6	19.9	49.7
	Copper	A	EE-12	31,200		4,500	3,000		52.5	73.5	10,000	42,200	79,300	35.2	5.7	39.3
	do	LA	HU-2.5	46,300	30,000	20,000	11,000	10,000	15.5	63.5		47,100	71,900	1.74	27.8	64.4
	21:78 nickel-copper alloy	A	HE-14	48,000	11,000	10,200	7,500	6,200	47.5	73.5	17,800	62,900	101,800	31.1	10.0	47.1
	do	LA	HE-4	62,500	46,000	45,000	37,000	25,000	23.0	68.0	25,500	65,600	115,600	4.87	38.9	54.0
	29:67 nickel-copper alloy	A	HZ-14.5	70,400	24,000	24,500	15,000	12,500	44.5	70.0	26,500	92,800	145,700	31.75	16.8	48.3
	do	LA	HZ-8.5	97,400	75,000	74,000	60,000	55,000	19.0	54.5	36,000	104,600	150,000	7.39	49.3	64.9
	40:57 nickel copper alloy	A	EH-14	71,500	25,000	26,500	22,500	20,000	47.5	67.5	30,000	94,000	159,800	31.28	16.6	44.7
	do	AR	EH	76,100	47,000	45,000	36,000	32,000	32.5	62.0	32,500	92,400	156,000	21.3	28.85	48.75
	Constantan	A	HP-12	66,000	22,000	22,500	21,000	20,000	47.5	78.5	30,000	86,800	227,700	31.5	9.9	29.1
	do	LA	HP-7.5	95,500	65,000	65,000	57,500	38,500	22.5	10.8	40,500	107,800	187,300	7.83	34.7	51.0
	Monel metal	A	EP-14	81,900	33,000	33,000	20,000	28,000	48.5	73.0	36,000	108,300	195,300	32.36	16.9	41.9
	do	LA	EP-8	127,000	97,000	90,000	85,000	85,000	21.5	59.5	52,000	139,200	211,600	9.56	42.5	60.0
	Nickel	A	EO-14	77,300	23,000	23,500	21,000	21,000	47.5	74.0	33,400	105,800	203,000	36.96	11.6	38.1
	do	LA	EO-6	130,800	91,000	85,000	80,000	80,000	16.5	35.5	50,400	145,500	175,700	11.3	48.3	74.7
	Copper-nickel-zinc alloy		CG	58,800	29,000	32,000	25,000	14,000	50.0	58.0		81,250	125,000	38.3	25.6	47.0
	Ambrac	HR	CD-14	51,100		13,000	9,000		47.5	72.9		68,500	135,200	33.9	9.6	37.8
	do	HR	CD	57,500		34,000	26,000		34.0	69.0	23,000	69,000	124,200	20.0	27.4	46.3
	Copper-nickel-tin alloy	A	CF-15	58,000		16,500	12,000		33.0	51.5	22,500	75,600	110,400	30.4	14.9	52.5
	do	CD	CF	90,500		54,000	14,000		4.0	23.5	33,500	91,300	107,800	0.85	50.5	83.9
	92:8 copper-tin alloy	A	EDA-12	56,500	20,500	20,500	19,000	18,000	81.0	73.0	21,000	93,200	153,600	65.05	13.3	36.8

[a] A, annealed; AR, as received; LA, low temperature anneal; OQ, oil quenched; T, tempered; WQ, water quenched.
[b] Usually the average for at least 4 specimens.

TABLE 3.—*Physical properties*—Continued

Comparison no.	Material	Condition	Designation	Tensile strength (TS)	Johnson's limit	Proof stress (PS)	Elastic limit	Proportional limit	Elongation in 2 inches	Reduction of area	Endurance limit	True stress at maximum load	True breaking stress (TBS)	Elongation at maximum load	Percentage ratio PS to TBS	Percentage ratio TS to TBS
				lb/sq in.	*lb/sq in.*	*lb/sq in.*	*lb/sq in.*	*lb/sq in.*	*Per cent*	*Per cent*	*lb/sq in.*	*lb/sq in.*	*lb/sq in.*	*Per cent*	*Per cent*	*Per cent*
	92:8 copper-tin alloy	AR	EDA	91,500	63,000	54,000	42,500	27,500	18.0	59.0		92,800	179,200	1.3	30.15	51.0
	90:10 copper-tin alloy	A	EC-12	63,500	17,500	18,500	17,000	15,000	76.0	72.0	20,500	102,500	175,000	61.75	10.6	36.25
	do	AR	ECA	95,300	57,500	51,500	40,000	30,000	22.5	56.5		105,260	173,500	10.43	29.7	54.9
	71:28 copper-zinc alloy	AR	MA	50,600	12,400	14,400	11,200	8,800	71.0	71.5		82,600	142,000	63.4	10.1	35.6
	65:35 copper-zinc alloy	A	EG-12	47,000	11,000	11,000	10,000	9,000	71.0	73.0	18,000	77,100	135,000	64.0	8.15	34.8
	do	LA	EG-4.5	83,000	65,000	60,000	40,000	32,500	15.0	61.0	24,800	85,800	144,800	3.2	41.4	57.3
	Aluminum bronze	AR	KE	79,500	34,000	37,000	21,000	18,000	33.5	31.9		100,800	115,200	26.8	32.1	69.0
	do	LA	KE-6	74,000	31,000	34,200	29,000	28,000	18.5	25.6	28,000	86,850	98,750	17.38	34.6	75.0
	do	A	BJB-11	62,000		31,500	15,000		25.0	24.0		74,800	81,550	20.64	26.4	76.1
	Tempalloy	AR	KBA	69,500	55,000	56,000	48,000	35,000	18.5	79.0		70,800	178,600	1.09	31.3	38.9
	do	LA	KBA-8	122,300	95,000	90,000	62,500	55,000	6.0	16.0	25,000	125,500	141,600	2.74	63.5	86.4
	Beryllium bronze	WQ	MT-14.26-W	66,500	16,250	17,500	9,750	9,750	38.0	31.9	25,000	95,200	97,600	43.0	17.9	68.1
	do	WQ and T	MT-W-4.5	85,000	42,500	41,000	35,000	33,500	18.0	21.3		98,300	101,400		40.4	83.8
	Aluminum	A	DR	12,600									34,000			37.0
	do	½ HT	DRA	16,000	13,000	12,000	7,500	7,500	25.0	75.0	7,300	16,700	32,000	4.78	37.5	50.0
	do	HT	DRB	20,400	16,000	16,000	14,000	11,500	18.5	64.0	8,400	20,350	33,500	4.13	47.7	60.9
	Aluminum - manganese alloy	A	DS	16,700	2,500	2,500	2,000	1,500	43.0	67.5	7,000	21,000	35,760	25.88	6.7	46.7
	do	½ HT	DSA	24,600	18,000	17,000	12,000	8,500	18.0	58.0	10,100	26,400	38,100	3.82	44.6	64.6
	do	HT	DSB	29,600	22,000	21,000	13,500	12,500	11.5	42.1	10,800	30,200	37,600	1.65	55.8	78.8
	do		JS	28,500	17,000	17,500	10,000	9,000	10.0	34.1	10,700	29,300	36,300	2.8	48.3	78.5
	Duralumin T		KI	62,700	30,500	31,000	29,000	28,000	26.0	39.8		74,700	94,200	19.1	32.9	66.6
	do	AR	GU	56,000	27,000	27,000	20,000	17,000	27.0	39.5	13,000	67,000	84,100	19.57	32.1	66.6
	do		LG	57,400	29,000	29,600	27,000	26,000	24.5	41.0		67,650	89,000		33.3	64.5
	do	AR	DU	33,300	20,000	20,000	18,000	15,000	18.0	42.5	13,500	36,400	49,200	9.31	40.7	67.6
	do	T	DUA	62,500	30,000	29,000	23,000	13,000	31.0	46.0		75,200	108,300	20.3	26.8	57.8
	do	T	GT	70,100	45,000	45,000	40,000	36,000	19.0	26.0	16,700	80,200	87,800	14.35	51.2	79.8
	do		KA	53,000	27,000	27,500	25,000	23,000	22.0	35.7	16,500	63,400	76,700	17.4	35.9	69.1
	do		JU	53,300	26,000	26,500	25,000	22,000	25.5	41.3	16,500	62,800	79,700	17.8	33.2	66.9
	Aluminum-copper alloy		DVA	59,000	30,000	30,000	25,000	19,000	23.5	41.2		66,100	88,100	13.9	34.0	67.0
	Aluminum - magnesium-silicon alloy		DTA	44,800	28,000	26,000	16,000	16,000	19.0	24.8	12,400	48,900	56,000	11.1	46.4	80.5
	do	AR	DTB	36,000	13,000	14,000	9,500	6,000	37.5	56.0	12,100	45,300	65,700	25.86	51.25	54.8
	Magnesium-aluminum alloy	AR	CN	39,800	20,000	18,300	13,000	12,500	16.0	20.0		44,000	47,900	10.0	38.2	83.1

WASHINGTON, August 14, 1934.